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SCS
NATIONAL
ENGINEERING
HANDBOOK

SECTION 15

IRRIGATION

Chapter 1

Soil-Plant-Water Relationships

March 1961

SOIL CONSERVATION SERVICE
UNITED STATES DEPARTMENT OF AGRICULTURE

The Soil Conservation Service National Engineering Handbook is intended primarily for Soil Conservation Service (SCS) engineers. Engineers working in related fields will find much of the information useful to them also.

This handbook is being published in sections, each section dealing with one of the many phases of engineering included in the soil and water conservation program. For easy handling, some of the sections are being published by chapters. Publishing of either sections or chapters is not necessarily in numerical order.

As sections or chapters are published, they will be offered for sale by the Superintendent of Documents, Government Printing Office, Washington, D.C. 20402, at the price shown in the particular handbook.

Section 15 of the handbook, Irrigation, is being published to supply engineers the basic data necessary to plan and maintain efficient conservation irrigation practices to provide a permanent irrigated agriculture. Engineering principles and research findings have been screened to give emphasis to the information needed to design, install, and operate irrigation systems on individual farms and groups of farms. Chapter 1, Soil-Plant-Water Relationships, describes those properties of soils and plants that affect the movement, retention, and use of the water essential to plant growth. Other chapters in this section have been developed according to policies and procedures of SCS and provide design criteria, design procedures, and methods of adapting engineering and research data to local irrigation problems. Numerous phases of irrigation engineering are included.

Chapters of Section 15 already published are listed below.

- Chapter 8. Irrigation Pumping Plants. Price 45 cents.
- Chapter 9. Measurement of Irrigation Water. Price 45 cents.
- Chapter 11. Sprinkler Irrigation. Price 55 cents.
- Chapter 12. Land Leveling. Price 60 cents.

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15 - IRRIGATION

CHAPTER 1 - SOIL-PLANT-WATER RELATIONSHIPS

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SCS NATIONAL ENGINEERING HANDBOOK

SECTION 15

IRRIGATION

CHAPTER 1--SOIL-PLANT-WATER RELATIONSHIPS

This chapter on soil-plant-water relationships treats those physical properties of soils and plants that affect the movement, retention, and use of water and that must be considered in designing and operating conservation irrigation systems.

In planning an irrigation system, an engineer is concerned primarily with the water-holding capacity of a soil, particularly in a plant's root zone; the water-intake rate of the soil; the root system of the crop to be grown; and the amount of water that the crop uses. But he must also have a working knowledge of all soil-plant-water relationships in order to plan efficient irrigation for particular crops grown on particular soils and to adjust the design to various conditions. This general knowledge also enables him to assist an irrigator in managing the system efficiently.

Soils

Soil is a storehouse of plant nutrients, a habitat for bacteria, an anchorage for plants, and a reservoir that holds the water needed for plant growth. The amount of water a soil can hold available for plant use is determined by its physical properties. This amount determines the length of time a plant can survive without water being added. It determines both the frequency of irrigation and the capacity of the irrigation system needed to insure continuous crop growth.

PHYSICAL PROPERTIES OF SOILS

Mineral soils are porous mixtures of inorganic (mineral) particles, decaying organic matter, air, and water. They also contain a variety of living organisms. The parent material of mineral soils consists of loose unconsolidated fragments of weathered rocks or unconsolidated sediments of various kinds. Physical and chemical weathering give rise to a horizontal layering in the soil mass. These different soil layers can be seen in trenches, eroded banks, and road cuts. Collectively these layers (horizons) from top to bottom are called the soil profile. Their arrangement and the kinds of material in the layers affect both root growth and the movement and retention of water in the soil.

Two important physical properties of soils are texture and structure. Soil texture refers to the relative proportion of the various size groups of mineral particles in a given soil. Soil structure refers to the manner in which the soil particles are arranged in groups or aggregates. Together, soil texture and soil structure help to determine the supply of water and air in a soil.

Soil Texture

The various size-groups of mineral particles in a soil are called separates. The classification of soil separates used by the U.S. Department of Agriculture and their range in diameter size are shown in the following list. Coarse fragments, those larger than 2 millimeters in diameter, are not included.

Soil separate:	<u>Particle diameter</u> (<u>millimeters</u>)	
Very coarse sand.....	2.0	- 1.0
Coarse sand.....	1.0	- .5
Medium sand.....	.5	- .25
Fine sand.....	.25	- .1
Very fine sand.....	.1	- .05
Silt.....	.05	- .002
Clay.....	Less than .002	

Soil textural classes are based on different combinations of sand, silt, and clay. For some kinds of work it is necessary to make fine distinctions in texture; the basic classes used in terms of size distribution as determined by mechanical analysis in the laboratory are shown graphically in figure 1-1. In some places it is convenient to speak more generally of texture; acceptable terms for groups of the basic classes are shown in table 1-1.

Table 1-1.--General terms for basic soil textural classes¹

General terms	Basic soil textural classes
Sandy soils.....	Coarse-textured soils.....Sands
	Loamy sands
Loamy soils.....	Moderately coarse textured soils..Sandy loam
	Fine sandy loam
	Medium-textured soils.....Very fine sandy loam
	Loam
	Silt loam
	Silt
	Moderately fine textured soils....Clay loam
	Sandy clay loam
	Silty clay loam
Clayey soils.....	Fine-textured soils.....Sandy clay
	Silty clay
	Clay

¹ From U.S. Dept. Agr. Handbook 18. Soil Survey Manual. 503 pp., illus. 1951.

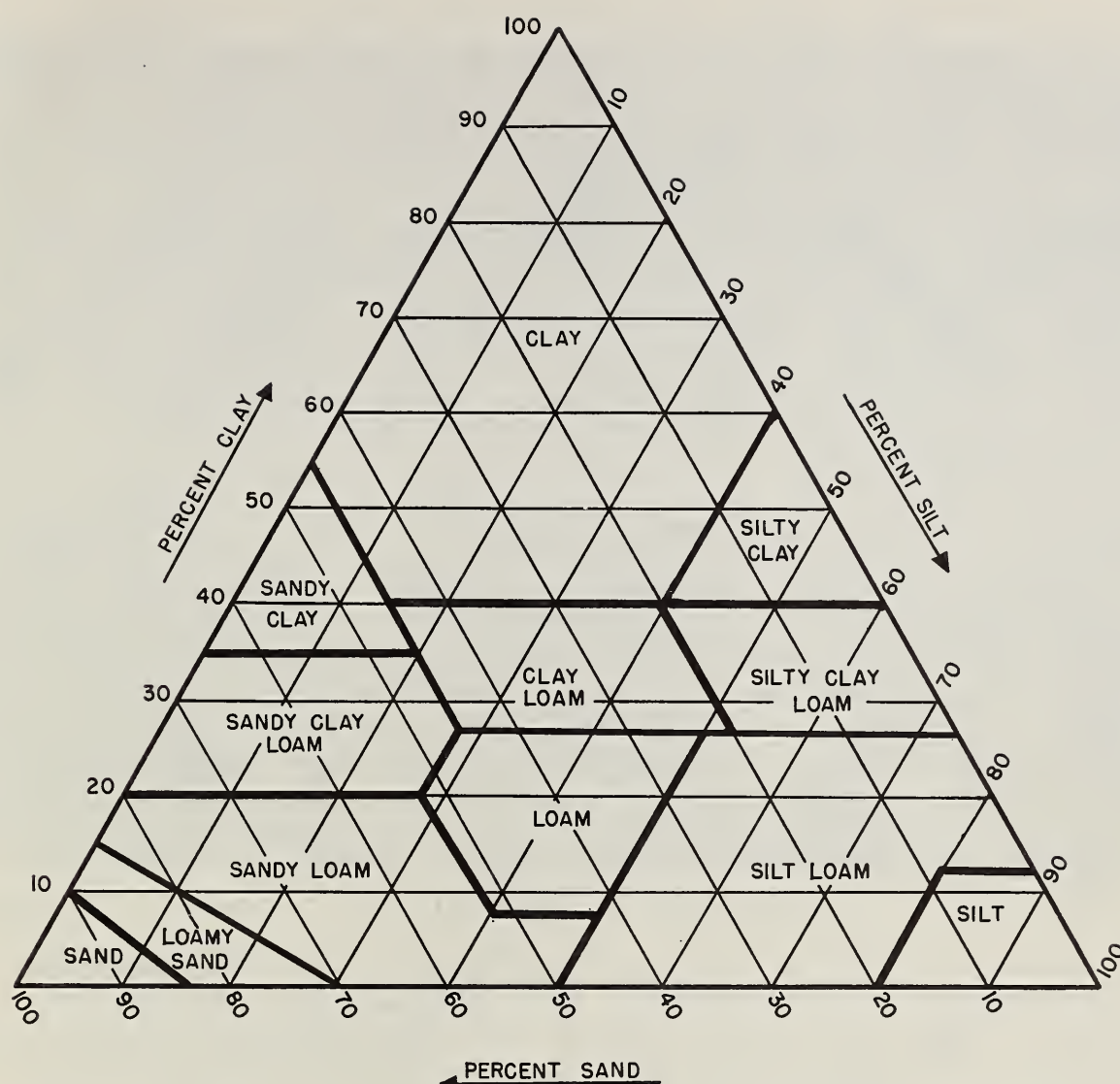


Figure 1-1.--Proportions of sand, silt, and clay in the basic soil-textural classes. (From U.S. Dept. Agr. Handb. 18. Soil Survey Manual. 503 pp., illus. 1951.)

In the field soil texture is determined by feeling the soil with the fingers. If necessary, this determination can be checked later in the laboratory. The general definitions of soil textural classes in terms of field experience and feel that are included in the USDA Soil Survey Manual follow.

SAND. Sand is loose and single grained. The individual grains can be seen or felt readily. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast but crumbles when touched.

SANDY LOAM. A sandy loam is soil containing a high percentage of sand but having enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. Squeezed when dry, a sandy loam forms a cast that falls apart readily. If squeezed when moist, a cast can be formed that bears careful handling without breaking.

LOAM. A loam is soil having a relatively even mixture of different grades of sand, silt, and clay. It is mellow with a somewhat gritty feel but is fairly smooth and slightly plastic. Squeezed when dry, it forms a cast that bears careful handling, and the cast formed by squeezing the moist soil can be handled freely without breaking.

SILT LOAM. A silt loam is soil having a moderate amount of fine sand and only a small amount of clay; over half of the particles are of the size called silt. When dry, a silt loam appears cloddy but the lumps can be broken readily; when pulverized, it feels soft and floury. When wet, the soil runs together readily and puddles. Either dry or moist, it forms a cast that can be handled freely without breaking; when moistened and squeezed between thumb and finger, it does not ribbon but has a broken appearance.

CLAY LOAM. A clay loam is fine-textured soil that usually breaks into clods or lumps that are hard when dry. When the moist soil is pinched between the thumb and finger, it forms a thin ribbon that breaks readily, barely sustaining its own weight. The moist soil is plastic and forms a cast that bears much handling. When kneaded in the hand, it does not crumble readily but works into a heavy compact mass.

CLAY. A clay is fine-textured soil that usually forms very hard lumps or clods when dry and is very plastic and usually sticky when wet. When the moist soil is pinched out between the thumb and finger, it forms a long, flexible ribbon. Some clays very high in colloids are friable and lack plasticity at all conditions of moisture.

Organic soils are soils in which the organic-matter content ranges from 20 percent to as high as 95 percent. They generally are classified on the basis of degree of decomposition of the organic deposits. Those deposits that are only slightly decayed or nondecayed are called peat; in peat soils the kinds of plants that make up the deposits can be identified. Well-decomposed deposits in which the original plant parts cannot be identified are called muck. The word mucky is used also as an adjective in the textural class name for horizons of mineral soils that contain 15 percent or more partially decomposed organic matter. Examples are mucky loam and mucky silt loam.

Soil Structure

Structure influences the rate at which water and air enter and move through the soil; it also affects root penetration and the soil's nutrient supply. Structure refers to the particular kind of particle grouping that predominates in a soil, but in many soils the kind of structure differs in different horizons.

Single-grained and massive soils are structureless. In single-grained soils such as loose sands, water percolates very rapidly. Water moves very slowly through massive soils. Of the four primary types of structure shown in figure 1-2--platy, prismatic, blocky, and granular--the

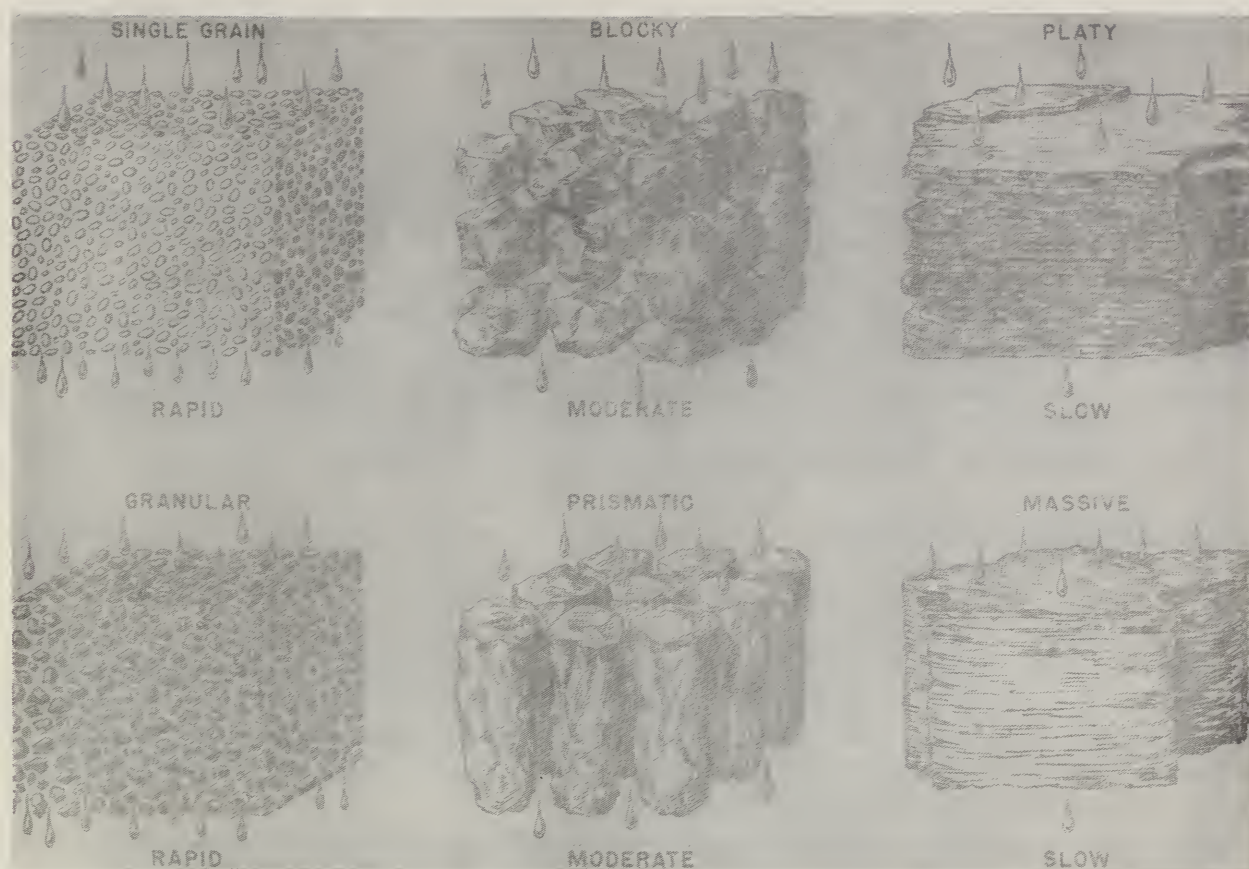


Figure 1-2.--Types of soil structure and their effect on downward movement of water. (From U.S. Dept. Agr. and U.S. Dept. Int. Agr. Inf. Handb. 199. Irrigation on Western Farms. 53 pp., illus. 1959.)

more favorable water relations are usually in soils that have prismatic, blocky, and granular structure. Platy structure impedes the downward movement of water.

Unlike texture, structure of the surface soil can be changed. Excellent structure develops in the surface layer of soils high in organic matter and on which a perennial grass is growing. Cycles of wetting and drying or of freezing and thawing improve structure in the plow layer. On the other hand, cultivation of medium- or fine-textured soils when their moisture content is high tends to destroy structure. Irrigation water containing large amounts of sodium causes very undesirable structure by dispersing the soil aggregates.

Tilth

The physical condition of the soil in relation to plant growth and ease of tillage is commonly called tilth. It depends partly on granulation and on stability of the granules. Tilth is commonly evaluated as good, fair, or poor, according to the ease with which the soil can be worked and the rate at which it takes in water. Soils in good tilth are mellow, crumbly, and easily worked; they take up water readily when dry. Soils in poor tilth generally are hard, cloddy, and difficult to work; they take up water slowly and run together when wet. Good soil tilth can be

developed and maintained on most soils by using good soil management practices.

SOIL WATER

Since a constant supply of water in the soil is necessary for plant survival and growth, the irrigation engineer is concerned with how water moves in a given soil, how much water a soil can hold and how much of it is available to plants, and how the water supply can be replenished. The first two are related to size and distribution of the soil pores and to size of the soil particles and their attraction for moisture. The amount of water a soil holds also depends on the amount of organic matter in the soil. Generally, the finer the soil particles and the larger the amount of organic matter, the more water a soil holds.

Kinds of Water in the Soil

The soil pores, spaces between the particles, form a network of connected cavities of every conceivable shape and size. When water is added to a dry soil by either rain or irrigation, it is distributed around the soil particles where it is held by adhesive and cohesive forces; it displaces air in the pore spaces and eventually fills the pores. When all the pores, large and small, are filled, the soil is said to be saturated and is at its maximum retentive capacity.

The water in the large pores that moves downward freely under the influence of gravity is called gravitational water or free water. When the supply of water to the surface is cut off, water continues to drain from the large pores for a few days. In well-drained soils, the free water near the surface usually has moved out before crops are damaged. The large pores are again filled with air; water in the small pores moves because of capillary forces and is called capillary water. It moves more slowly than free water; it can move in any direction but always in the direction of the greatest tension.

Evaporation from the surface and absorption of moisture by growing plants further reduce the amount of water in the soil until water no longer moves because of capillary forces. It is held so tightly as very thin films around the soil particles and in minute wedges between the particles at their points of contact that it cannot be used by plants and they begin to wilt. Eventually the soil is so dry that plants die if water is not added to the soil. The remaining water is held on the particle surfaces, particularly the soil colloids, so tightly that much of it is nonliquid and moves as a vapor. This is called hygroscopic water.

Of these three forms of water, gravitational, capillary, and hygroscopic, the irrigation engineer is concerned primarily with gravitational and capillary water since hygroscopic water is not available to plants.

Movement of Water in the Soil

The movement of water in the soil is complex because of the various states and directions in which water moves and because of the forces that cause it to move. Because of gravity, water moves downward. Because of adhesive and cohesive forces, it moves in small pores by capillarity. Because of heat, it vaporizes and diffuses through the soil air.

The rate at which gravitational water percolates through the soil is determined chiefly by the size and continuity of the pore spaces. Water usually moves freely through the large pores in coarse-textured soils. It moves less rapidly through fine-textured soils because of the resistance to flow in small pores, which may also be blocked by swollen colloidal gels and trapped air. Percolation is retarded by a slowly permeable layer such as a claypan or plowpan. A sand lens temporarily halts percolation; but once water penetrates such a layer, it continues to move downward. These different conditions are illustrated in figure 1-3.

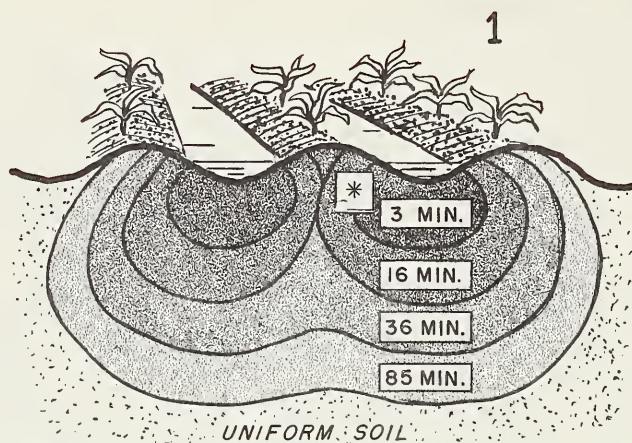
Irrigation water moves as a front--from a saturated soil layer to an unsaturated layer. Movement of the front is unsteady; water builds up behind the front until the large pores are filled and then moves to the next layer of large pores. In moist soils water movement is more uniform than in dry soils.

The movement of capillary water is affected by soil texture. The forces that cause capillary movement in small pores result largely from the difference in tension between films of different thickness around soil particles; the movement is from thick films to thin films. If these forces are expressed in terms of tension, water moves from an area where tension is low to an area where tension is high. At saturation, capillary movement is most rapid in sandy soils and slowest in clay soils. But in drier or unsaturated soils capillary water moves slowly in sands and more rapidly in clays.

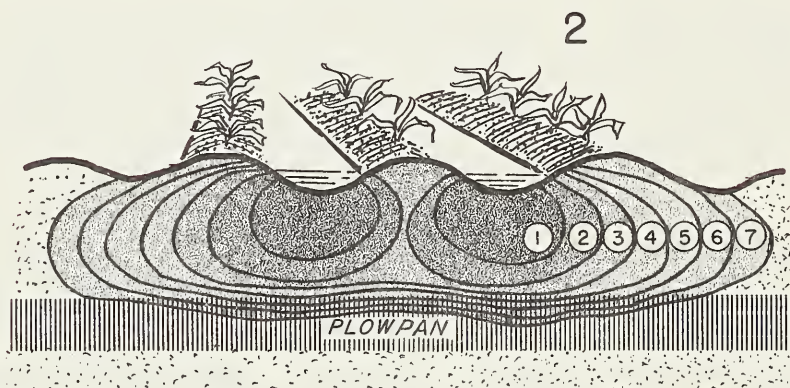
Heat causes water to move as a vapor. As water vapor diffuses through the soil air near the surface, it either condenses in another part of the pore space or escapes into the atmosphere. As water is evaporated from the surface, capillary water rises and replaces part of the evaporated water. This continues until the upper few inches of the soil become dry and capillarity is broken. Water then leaves the soil only by vaporizing at the upper capillary fringe and diffusing through the overlying dry soil.

How Water Is Held in the Soil

Work must be done (energy used) to remove water from a soil. The force (tension) with which water is held depends on the amount in the soil--the smaller the amount, the greater the tension. The forces that determine tension are adhesion, the attraction of soil-particle surfaces for water, and cohesion, the attraction of water molecules for each other. By adhesion water is held tightly at the soil-water interface. By cohesion these

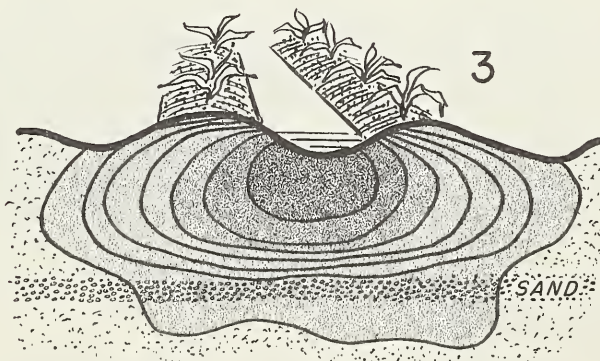


WATER PENETRATION IN UNIFORM SOIL



* ① 13 MIN. ② 22 MIN. ③ 40 MIN. ④ 64 MIN. ⑤ 74 MIN. ⑥ 125 MIN. ⑦ 196 MIN.

EFFECT OF A PLOW/PAN ON WATER PENETRATION



EFFECT OF A SAND LENS ON WATER PENETRATION

* TIME IN MINUTES SHOWN IN SKETCHES IS THE ELAPSED TIME FROM START OF WATER APPLICATION.

Figure 1-3.--Examples of water penetration from an irrigation furrow.

water molecules hold other water molecules. Because of these forces water fills the small pores in the soil and is in fairly thick films in the large pores. As the films become thicker, however, the water molecules at the outer surface, the liquid-air interface, are held less tightly. They can move in response to the pull of gravity and to the pull of less thick films nearby. Thus not much work or energy is required to remove water from a soil near saturation. But as more and more water is removed, more and more energy is required.

SOIL-MOISTURE TENSION. Soil-moisture tension is a measure of the tenacity with which water is retained in the soil and shows the force per unit area that must be exerted to remove water from a soil. It is usually expressed in atmospheres, the average air pressure at sea level, but other pressure units can be used. At a temperature of 21°C . (69.8°F .),

1 atmosphere = a pressure of 14.71 pounds per square inch,
 = a column height of 76.39 centimeters of
 mercury
 = a column height of 34.01 feet or 1,036
 centimeters of water.

An expression of soil-moisture tension does not indicate the amount of water a soil contains nor does it indicate the amount of water that can be removed at that tension. These amounts, which depend on both texture and structure, must be determined. Generally sandy soils drain almost completely at low tension, but fine-textured clays still hold a considerable amount of moisture even at such high tensions that plants growing in the soil wilt.

To show the amount of moisture a given soil holds at various tensions, moisture-extraction curves must be developed. This can be done by plotting tension in atmospheres against moisture content in percentage by weight. Tension values indicate the ease or difficulty with which moisture can be removed from a soil, and moisture percentage indicates the amount of water still in the soil.

Figure 1-4 shows moisture-extraction curves, also called moisture-characteristic curves, for three soils of different texture. The curve for the clay shows that moisture is released in fairly even increments as tension increases. The curve for the sand shows a proportionately greater release of moisture at low tension than the curve for the clay. The curve for the loam is intermediate in shape between the curves for the clay and the sand.

Soil-moisture tension as discussed in the preceding paragraphs is based on pure water. Salts in soil water increase the force that must be exerted to extract water and thus affect the amount of water available to plants. The increase in tension caused by salts is from osmotic pressure. If two solutions differing in concentration are separated by a membrane impermeable to the dissolved substance, such as a cell membrane

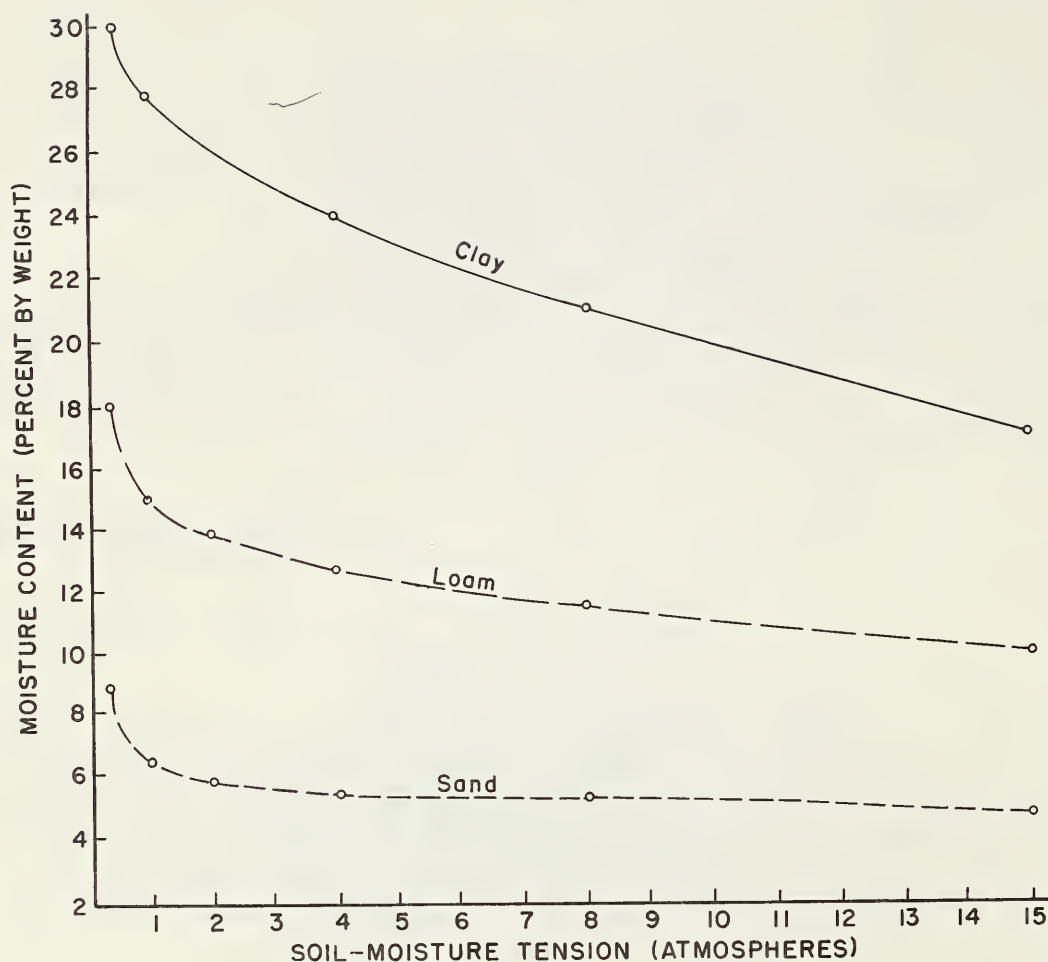


Figure 1-4.--Moisture-characteristic curves. (From Thorne, M.D., and Raney, W. A. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6. 14 pp., illus. 1956.)

in a plant root, water moves from the solution of lower concentration to the one of higher concentration. The force with which water moves across such a membrane is called osmotic pressure and is measured in atmospheres.

In many irrigated soils, the soil solution contains an appreciable amount of salts. The osmotic pressure developed by the soil solution retards the uptake of water by plants since the total moisture stress is the sum of the soil-moisture tension and the osmotic pressure of the soil solution. Plants growing in a soil in which the soil-moisture tension is 1 atmosphere apparently can extract enough moisture for good growth. But if the osmotic pressure of the soil solution is 10 atmospheres, the total stress is 11 atmospheres and plants cannot extract enough water for good growth.

Available Water

In designing an irrigation system and in making recommendations for improved techniques of applying water, the engineer needs to know how much of the water in a soil is available to plants. The soil is like a

tank and holds just so much available water. Its capacity is limited by the total amount of water it can hold between field capacity and the permanent wilting point (fig. 1-5). In addition to soil-moisture tension and the osmotic pressure of the soil solution, availability of water also depends on the temperature of the soil. Low soil temperatures decrease availability.

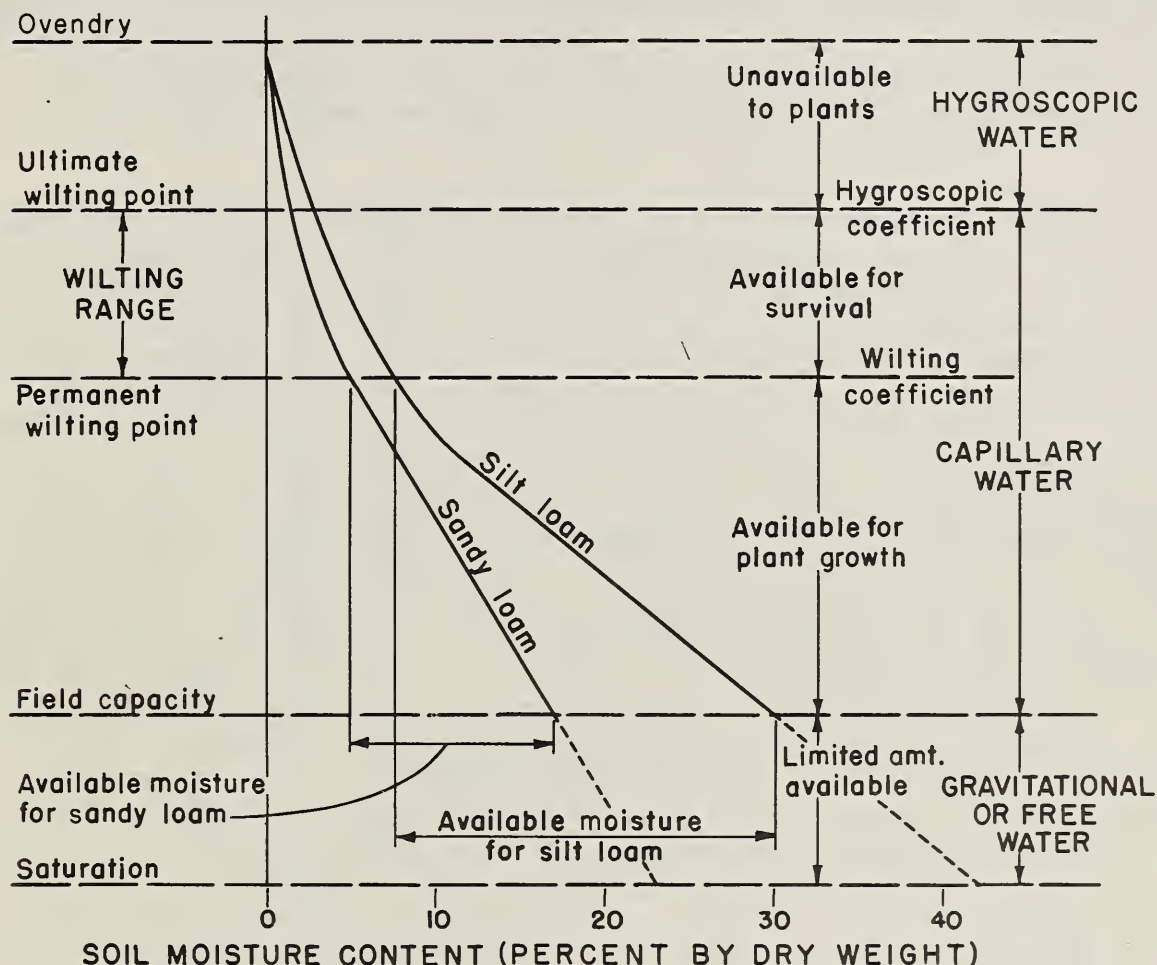


Figure 1-5.--Kinds of water in the soil and difference in available-moisture content between a sandy loam and a silt loam. The silt loam contains more than twice as much readily available water.

Field capacity is usually considered as the amount of water a well-drained soil holds after free water has drained off or the maximum amount it can hold against gravity. The large pores in the soil are filled with air, the micropores are filled with water, and any further drainage is slow. In this condition, the soil is said to be at field capacity.

Soil-moisture tension in a salt-free soil at field capacity ranges from less than 0.1 to nearly 0.7 atmosphere, depending on soil texture. Research shows that sands are at field capacity when tension is near 0.06 atmosphere, and loamy sands, such as those in the Norfolk, Lakeland,

Tifton, Atwater, and Tujunga series, when tension is near 0.1 atmosphere. Silt loams, such as those in the Muscatine, Flanagan, Honcut, and Merced series, are at field capacity when tension is about 0.3 atmosphere. Clays and clayey soils, such as those in the Paulding, Varco, Sharkey, Bladen, and Rossi series, are at field capacity when tension is about 0.6 atmosphere.

Field capacity of a soil can be determined, after it has been thoroughly wetted by rain or irrigation water, by covering a small area to prevent evaporation and determining the moisture content after drainage has taken place. One method is to take soil samples, weigh them, dry them in the oven, and reweigh them.

The permanent wilting point, also known as permanent wilting percentage, is the soil-moisture content at which plants can no longer obtain enough moisture to meet transpiration requirements; they wilt and remain wilted unless water is added to the soil. The moisture tension of a soil at the permanent wilting point ranges from 7 to 32 atmospheres, depending on soil texture, on the kind and condition of the plants, on the amount of soluble salts in the soil solution, and to some extent on the climatic environment. Since this point is reached when a change in tension produces little change in moisture content, there is little difference in moisture percentage regardless of the tension taken as the permanent wilting point. Therefore 15 atmospheres is the pressure commonly used for this point. During periods of low humidity, high temperature, and high wind velocity many plants with a large leaf surface show wilting even though the moisture content of the soil is higher than that at the permanent wilting point. This occurs because the transpiration rate exceeds the rate at which the plant can extract moisture from the soil. When a plant wilts, growth stops. Irrigation water, therefore, should always be applied to a soil before the moisture content of the root zone is reduced to the permanent wilting point.

The wilting range is the range in soil-moisture content through which plants undergo progressive degrees of permanent or irreversible wilting, from wilting of the oldest leaves to complete wilting of all leaves. At the permanent wilting point, which is the top of this range, plant growth ceases. Small amounts of water can be removed from the soil by plants after growth ceases, but apparently the water is only slowly absorbed and is only enough to maintain life until more water is available. The bottom of the range is called the ultimate wilting point. When the moisture level reaches this point, wilting is complete and plants die. Although the difference in the amount of water in the soil between the two points may be small, there may be a big difference in tension. At the ultimate wilting point soil-moisture tension may be as high as 60 atmospheres.

Since the moisture available for plant growth is the capillary water between field capacity and the permanent wilting point, the available water holding capacity of a soil can be determined by subtracting the amount of moisture remaining in the soil at the permanent wilting point from the amount held at field capacity.

Soil texture is of primary importance. For soils low in soluble salts, the finer the texture, the greater the available moisture holding capacity. Figure 1-6 shows the difference in soil-moisture content of a sandy loam and a silt loam at the same tension. But some sandy soils actually hold more available water than some clays, chiefly because in fine-textured soils so much water is held on the particles. Even at the permanent wilting point, the moisture content of some clays is fairly high.

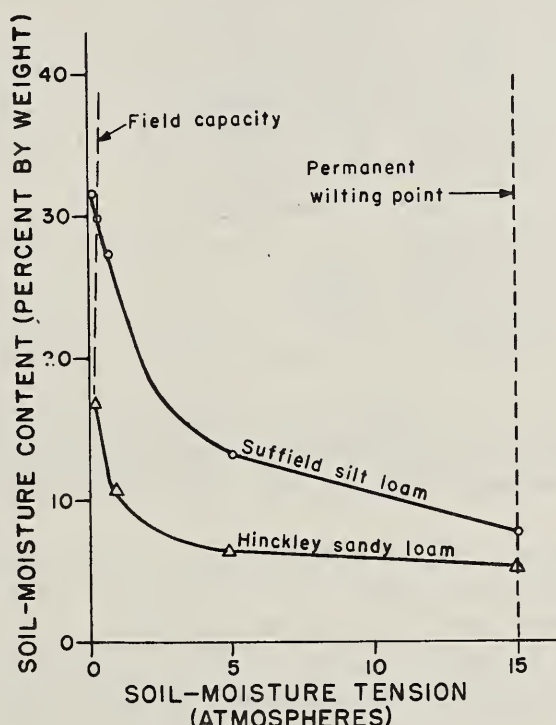


Figure 1-6.--Relation between soil-moisture content and soil-moisture tension in a sandy loam and a silt loam.

Well-drained sandy soils have a low available water holding capacity. At field capacity, most of the pore space in sandy soils is filled with air and thus there is little available moisture. Silty soils generally have a good available water holding capacity since a soil made up of silty particles of about the same size releases most of its moisture at tensions ranging from one-third atmosphere to 15 atmospheres. But in some silty soils the spaces between large particles may be filled with smaller particles, resulting in a low available moisture holding capacity. Some silt loams hold more than 2 inches of available moisture per foot of soil, but some silty soils are very droughty. Clays and clay loams are usually high in available water--about 2 inches per foot of soil--and still hold a considerable amount of unavailable moisture at the wilting point. Organic soils hold a considerable amount of water at field capacity, but since much of the water is not available, they also have a high moisture content at the wilting point.

The range in available moisture holding capacity common in soils of different texture is given in the following list.

	<u>Inches of water per foot of soil</u>
Very coarse texture--very coarse sands.....	0.40 - 0.75
Coarse texture--coarse sands, fine sands, and loamy sands.....	.75 - 1.25
Moderately coarse texture--sandy loams and fine sandy loams.....	1.25 - 1.75
Medium texture--very fine sandy loams, loams, and silt loams.....	1.50 - 2.30
Moderately fine texture--clay loams, silty clay loams, and sandy clay loams.....	1.75 - 2.50
Fine texture--sandy clays, silty clays, and clays.....	1.60 - 2.50
Peats and mucks.....	2.00 - 3.00

Since accurate evaluation of available moisture is extremely important in designing and operating an irrigation system, available moisture should always be measured or measurements from comparable soils used.

So far in this discussion, field capacity has been considered the upper limit of available moisture. This is not entirely true. In sprinkler and surface irrigation, water applied to the surface of the soil moves downward as a front, saturating the upper layers in most soils before the irrigation application is completed. Plant roots in the upper soil layers take up some of the water between saturation and field capacity. The amount plants use depends on how fast the soil drains to field capacity and on how often it is irrigated. Under good irrigation management on most soils, the length of time in which plants can use the extra moisture before the soil reaches field capacity is limited. For design purposes, therefore, this water is not considered.

Calculating Available Water

The available water in a soil can be calculated if the moisture content (percentage) and physical properties of the various horizons are known. Table 1-2 shows the moisture content of a Hinckley loamy sand at different tensions and table 1-3, its physical properties.

Table 1-2.--Moisture content of a Hinckley loamy sand at various tensions

Horizon	Depth	Moisture content at tension of--					Available water	
		1/10 ¹ atmos.	1/3 atmos.	2/3 atmos.	5 atmos.	15 ² atmos.	In soil	In horizon
	<u>In.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>Pct.</u>	<u>In. per in.</u>	<u>In.</u>
Ap.....	0- 8	21.1	13.7	12.5	8.3	8.3	0.147	1.18
B ₂₁	8-14	22.5	16.9	13.8	8.7	8.7	.173	1.04
B ₂₂	14-20	17.0	13.2	10.8	6.2	5.1	.146	.88
C.....	20-26	9.8	7.6	5.8	3.9	3.0	.095	.57
D.....	26-32	6.0	5.5	3.0	2.0	1.4	.068	.41
							Total--	4.08

¹ Field capacity.² Wilting point.Table 1-3.--Physical properties of a Hinckley loamy sand
(Soil analysis by Agricultural Research Service)

Horizon	Depth	Bulk density	Particle-size distribution			Textural class	Organic matter
			Sand	Silt	Clay		
	<u>Inches</u>		<u>Percent</u>	<u>Percent</u>	<u>Percent</u>		<u>Percent</u>
Ap.....	0- 8	1.15	80.6	16.9	2.5	Loamy sand	3.57
B ₂₁	8-14	1.25	76.8	20.7	2.5	Loamy sand	1.90
B ₂₂	14-20	1.23	78.7	18.8	2.5	Loamy sand	1.02
C.....	20-26	1.39	86.8	10.7	2.5	Sand	.62
D.....	26-32	1.47	95.0	2.5	2.5	Sand	.25

For irrigation, moisture content is expressed preferably in inches of water per inch of soil or in inches of water per foot of soil instead of percentage by weight. To convert soil-moisture content from percentage by weight to a volume basis, the following equation can be used.

$$D = \frac{d_b \times d \times P_w}{d_w \times 100}$$

Where D = inches of water in soil depth (d)

d_b = bulk density $\left(\frac{\text{weight of oven-dry soil in grams}}{\text{field volume of sample in cubic centimeters}} \right)$

d = depth of soil sample in inches

P_w = moisture content between field capacity and wilting point in percentage by weight

d_w = density of water taken as 1

The last two columns in table 1-2 were calculated by using this formula. For example, the available-moisture content of the Ap horizon is calculated from data in tables 1-2 and 1-3 for a soil depth of 1 inch as follows:

d_b = 1.15 (from table 1-3)

d = 1 inch

d_w = 1

P_w = 21.1 - 8.3 = 12.8 (table 1-2)

$D = \frac{1.15 \times 1 \times 12.8}{1 \times 100} = 0.147 \text{ inch}$

Therefore, the total available water in the Ap horizon, which is 8 inches deep, is 0.147 x 8, or 1.18 inches.

For irrigation-system design, the total available water is calculated for a soil depth based on the root system of a mature plant of the crop to be grown. For any soil this amount is different for different crops, depending on their rooting characteristics. Root systems of plants are discussed on pages 1-29 to 1-31. The total amount of available water in the 32-inch depth of the soil shown in table 1-2, for example, is 4.08 inches, the sum of that in the five horizons. If a shallow-rooted crop growing in this soil were to be irrigated to a 20-inch depth, the total amount of available water could be determined by adding the amount that can be held in horizons Ap, B21, and B22, which is 1.18 + 1.04 + 0.88, or 3.10 inches.

WATER INTAKE

The movement of irrigation water from the surface into and through the soil is called water intake. It is the expression of several factors, including infiltration and percolation.

Infiltration

The downward flow of water from the surface into the soil is known as infiltration. Water enters the soil through pores, cracks, worm and decayed-root holes, and cavities introduced by tillage. In many places infiltration is restricted by surface sealing or crusting.

Percolation

For irrigation water to be effective in replenishing the soil's water supply, it must be able to move down, or percolate, through the soil to a predetermined irrigation depth. This movement of water through the soil profile is known as percolation. The percolation rate is governed by the permeability of the soil or its hydraulic conductivity. Both terms are used to describe the ease with which soil transmits water.

Permeability is the quality of soil that enables it to transmit air and water. It is independent of the viscosity of water. The relative permeability of soils is described in general terms as rapid, moderate, and slow.

Hydraulic conductivity is determined by both the soil and the fluid transmitted. It expresses the readiness of a soil to let a particular fluid flow through it for a given potential gradient. It is the coefficient "k" in Darcy's Law ($v = ki$) in which v is the effective flow velocity and i is the hydraulic gradient. The values of k depend on the properties of the fluid as well as on those of the soil, and they reflect any interactions of the fluid with the porous medium, such as swelling of a soil and the attendant reduced porosity.

Since water percolates chiefly through the large pores in a soil, percolation depends on the relative number and continuity of these pores. A soil that has high porosity and coarse open texture has a high hydraulic-conductivity value. For two soils of the same "total" porosity, the soil with small pores has lower conductivity than the soil with large pores because of the resistance to flow in small pores. A soil with pores of many sizes conducts water faster if the large pores form a continuous path through the profile. In fine-textured soils, conductivity depends almost entirely on structural pores. In some soils, particles are cemented together to form nearly impermeable layers commonly called hardpans. In other soils, very finely divided or colloidal material expands on absorbing water to form an impervious gelatinous mass that restricts the movement of water.

The quality of the water transmitted, particularly its salinity and alkalinity, has a marked effect on hydraulic conductivity. A change in the viscosity of water has an effect. A chemical change in water may greatly affect hydraulic conductivity without changing viscosity. The addition of a small amount of sodium chloride to the soil water, insufficient to make any noticeable difference in viscosity, may affect soil structure so much that hydraulic conductivity is greatly reduced.

Factors Affecting Intake Rate

The intake rate of a soil is a measure of its capacity to take in and absorb irrigation water applied to the soil surface during the period of time in which water is applied. The amount of moisture already in the soil greatly influences the rate at which water enters the soil. The soil takes in and absorbs irrigation water rapidly when water is first applied to the field surface. As the irrigation application continues, the surface soil gradually becomes saturated and the intake rate decreases until it reaches a nearly constant value.

The intake rate of any soil is limited by any restriction to the flow of water into or through the soil profile. The soil layer with the lowest transmission rate, either at the surface or below it, usually determines intake rate. The most important general factors that influence intake rate are the physical properties of the soil and in sprinkler irrigation the plant cover. But for any given soil other factors may affect the intake rate.

SURFACE SEALING. The formation of a thin compact layer on the ground surface rapidly reduces the rate of water intake through the surface. This layer results from a breakdown in structure, in part because of the beating action of raindrops or sprinkler drops and in part because of the action of water flowing over the surface whereby fine particles are fitted around larger particles to form a relatively impervious seal.

The effect of surface sealing on intake can be greatly reduced, if not eliminated, by protecting the soil surface with a mulch or some other permeable material. Grasses or other close-growing vegetation will help to prevent surface sealing. The hardened or compact surface of a soil subject to surface sealing can be broken up by a light cultivation before irrigation water is applied.

SOIL COMPACTION. On some wet soils tillage operations may cause compaction and the formation of a plowpan just below cultivation depth. A plowpan impedes water movement and reduces the intake rate. The intake rate is materially reduced in furrows where tractor wheels operate. Subsoiling helps to improve the movement of water through a plowpan and thus the intake rate, particularly in soils that have a relatively impermeable sublayer that can be broken up. The soil takes in more water through the enlarged openings and continues to take in water so long as they remain.

SOIL CRACKING. On heavy clay soils that crack on drying, irrigation generally can be accomplished by rapidly filling the cracks before the soil starts to swell. The amount of water that can be applied depends on the number and size of the cracks. As soon as the soil particles become wet, they begin to swell; eventually the cracks are closed so that further intake is either impossible or extremely slow.

TILLAGE. The intake rate may be increased by plowing, cultivating, or any other stirring that increases the size of openings. But the beneficial effect of cultivation on soil porosity and intake lasts only until the soil settles back to its former condition of density because of subsequent rain or irrigation. The intake rate of loose, porous sands is not likely to be increased by any artificial disturbance. On some soils, cultivation reduces intake by closing up the natural surface openings that lead into the body of the soil. The most important effect of tillage on water movement is to break up a surface seal.

CROP ROTATIONS. If coarse organic materials are evenly incorporated into the soil, porosity remains high for comparatively long periods, depending mostly on the rate of decomposition of the materials. The intake rate can be maintained and even increased by using a cropping system that provides for incorporating crop residues in the upper few inches of the soil, growing grasses and legumes, and using any other methods that increase the organic-matter content of the soil. If a good crop rotation is followed, the proportion of stable soil aggregates is increased, which means large pores and consequently a high water-intake rate.

SOIL AND WATER SALTS. Any salts contained in irrigation water accumulate in irrigated soils and in time may change their character. This accumulation is serious in the arid West where almost all water is supplied by irrigation. In humid areas rainwater percolating through the soil leaches out most accumulated substances. But in arid regions it is often necessary to overirrigate (leach) periodically to remove soluble salts from the soil.

Some soluble salts in irrigation water such as potassium nitrate may be directly beneficial to crops. Under some conditions, calcium and magnesium have a beneficial effect on the physical condition of the soil. High concentrations of sodium chloride or sodium sulfate, however, have a detrimental effect. If the sodium concentration is high, soil structure breaks down and eventually the soil colloids are dispersed, resulting in a tough or rubbery condition. Tilth and permeability are reduced. This sealing is noticeable even in some sandy soils.

The physical properties of some alkali soils, including intake, can be improved by adding chemicals or soil amendments through which exchangeable sodium is replaced by calcium. A comparatively economical and often used soil amendment is calcium sulfate, or gypsum. In some soils, its use results in improved permeability and aeration and thus better root development and plant growth. Other chemicals that can be used on some soils are sulfur and aluminum sulfate.

SEDIMENTS IN IRRIGATION WATER. In some places, fine silt and clay particles carried in suspension affect the quality of irrigation water. Whether this is detrimental or beneficial depends on the amount of silt transported, the length of time the silty flow continues, and the texture of the soil to which the water is applied. Occasional deliveries of silty water may be beneficial on coarse sandy soils inasmuch as the sediments improve the physical condition of the root zone, thereby reducing the rate of water movement. They also add some plant nutrients such as potassium, calcium, and phosphates to the soil. But silty water applied to fine-textured soils generally makes the surface of the soil still more slowly permeable and difficult to cultivate.

SOIL EROSION. As erosion progresses, the intake rate of many soils is reduced since less permeable material such as a dense clay subsoil is uncovered. In other soils erosion exposes coarse-textured layers such as sand and gravel. Here the intake rate is increased and irrigation efficiency is greatly reduced.

LAND LEVELING. The moving and mixing of soil in land leveling may change the water-intake rate of any given area. The effects are similar to those of erosion in that either more permeable or less permeable soil material is uncovered. Earth-moving equipment used in land leveling may compact the soil and thereby reduce the intake rate. Subsoiling is often necessary after land leveling.

TEMPERATURE. Tests show that water intake is greater during summer rains than during winter rains. Apparently the temperature of irrigation water has some effect on intake rate since the coefficient of viscosity of water decreases rapidly as temperatures increase. This effect is not considered significant by most authorities.

Variation in Intake Rate by Irrigation Method

The water-intake rate varies with the method of water application (fig. 1-7). Since sprinkler irrigation is similar to rainfall, a soil's intake rate under this method is modified by the amount of cover. Bare fields, fields newly seeded, and fields in row crops take in water more slowly than fields that have a good grass-legume crop or mulch cover. Soils that are subject to surface sealing under rainfall are likely to seal under sprinkler irrigation. For sprinkler irrigation, intake rate is expressed in inches per hour.

In partial-flooding methods, water is applied by running small streams in furrows or corrugations and only a part of the soil surface is flooded. Water moves both downward and outward from a furrow, and the intake rate depends on the capacity of the soil to transmit water both vertically and laterally. The intake rate depends also on the wetted perimeter of the furrow. It is higher in furrows having large wetted perimeters than in furrows having small wetted perimeters. For furrow irrigation, the intake rate usually is expressed in gallons per minute per 100 feet of furrow.

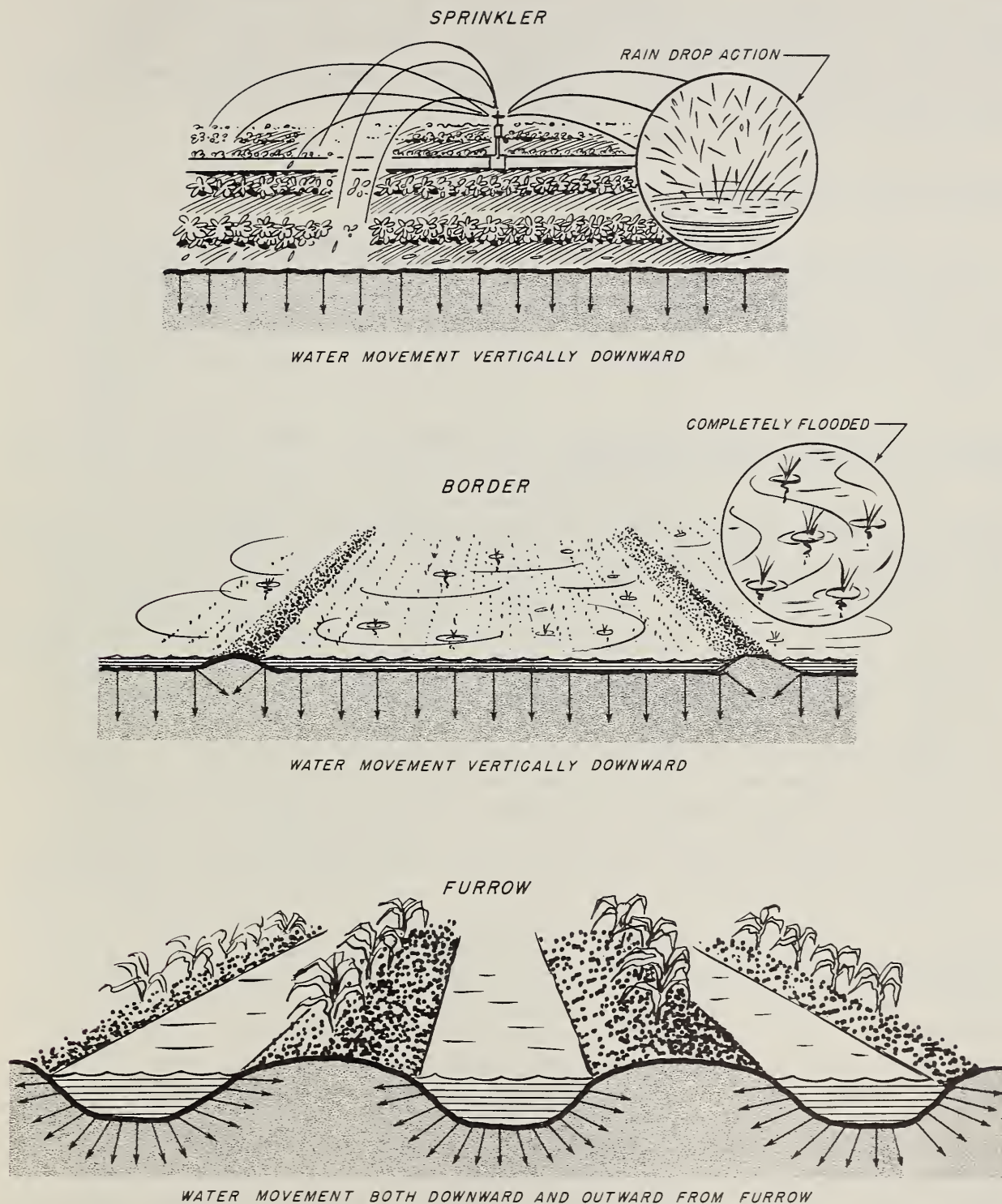


Figure 1-7.--Water-intake rate varies with method of irrigation.

Under flooding methods--border, contour levee, and contour ditch--the surface of the soil is completely flooded. Water moves into the soil vertically. Although depth of flooding has some effect on the intake rate, it is generally ignored in designing an irrigation system because the effect is so small. For flooding methods, the intake rate is expressed in inches per hour.

Intake Characteristics

Since so many factors affect water intake, it is not surprising that it varies so much among soils. Furthermore, the intake characteristics of a given field vary from place to place, from irrigation to irrigation, and from season to season. The intake characteristics that must be considered in sprinkler-irrigation design differ from those for surface methods.

RELATION OF TOTAL INTAKE TO TIME. This relation is an expression of the time (measured from the beginning of an irrigation application) required for a soil to absorb a specified amount of water. A knowledge of the relation between time and total intake is especially important in surface methods of irrigation. Figure 1-8 shows this relation for three soils, representing a high, a moderate, and a low intake rate. The soil that has a moderate intake rate absorbs 3 inches of water in about 1-3/4 hours. For a 3-inch application it can be concluded that an irrigator in flooding his land would waste water if he applied water for longer than 1-3/4 hours. This same soil needs to be wetted for only one-third of an hour for a 1-inch application and for about 4-1/2 hours for a 6-inch application. The irrigator can control amount of intake by varying the length of time water flows over the field. This relation between total intake and time helps to determine the speed with which the wet front advances across a field and thus to a great degree controls the permissible length of run. Curves to show this relation can be developed by following the procedures outlined under methods of determining intake.

RELATION OF INTAKE RATE TO TIME. This relation is an expression of the instantaneous rate (inches per hour) at which water enters the soil measured at some time after the application is started. It is especially important in sprinkler irrigation and in surface methods where the stream size varies. Figure 1-9 shows this relation for the same soils shown in figure 1-8.

Note that at the start of irrigation the intake rate is high but that it declines rapidly. After some time, it reaches a point beyond which it changes very little. A comparison of figures 1-8 and 1-9 shows that the high-intake-rate soil absorbs 3 inches of water in about one-third of an hour and that at the end of that time the intake rate has declined to about 4.6 inches per hour. The moderate-intake-rate soil absorbs 3 inches in 1-3/4 hours, by which time the intake rate has declined to about 1.2 inches per hour. In the low-intake-rate soil, the total time is 6-1/2 hours, by which time the rate is 0.3 inch per hour. The relative position on the intake-rate curve at the time irrigation is completed is markedly

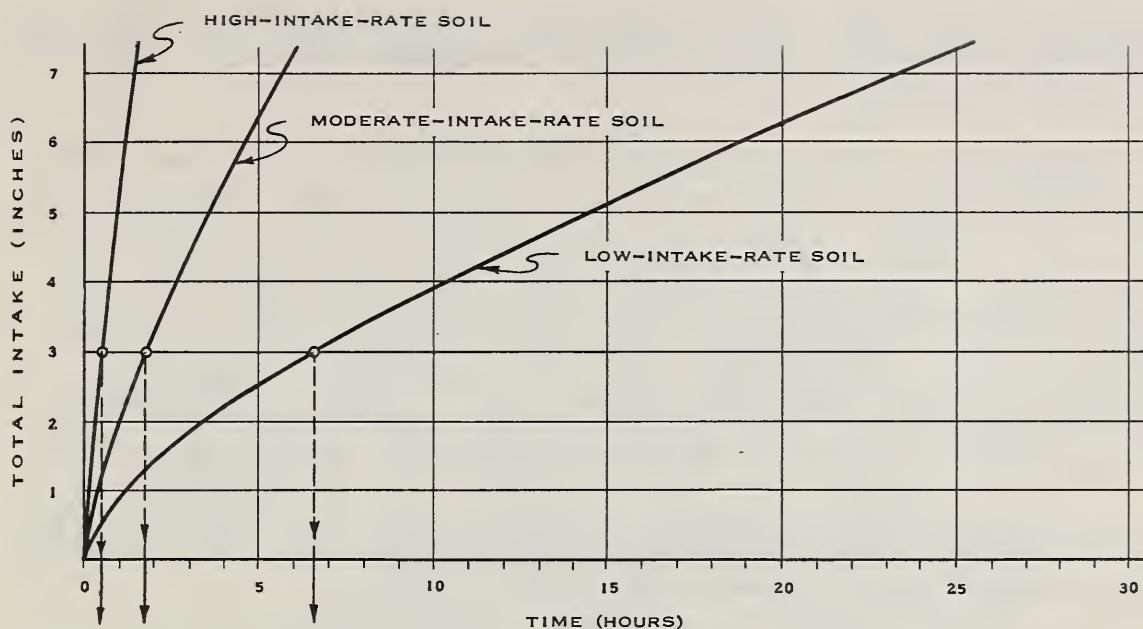


Figure 1-8.--Relation of total intake to time for three soils. A 3-inch application is absorbed by the high-intake-rate soil in one-third of an hour, by the moderate-intake-rate soil in 1-3/4 hours, and by the low-intake-rate soil in 6-1/2 hours.

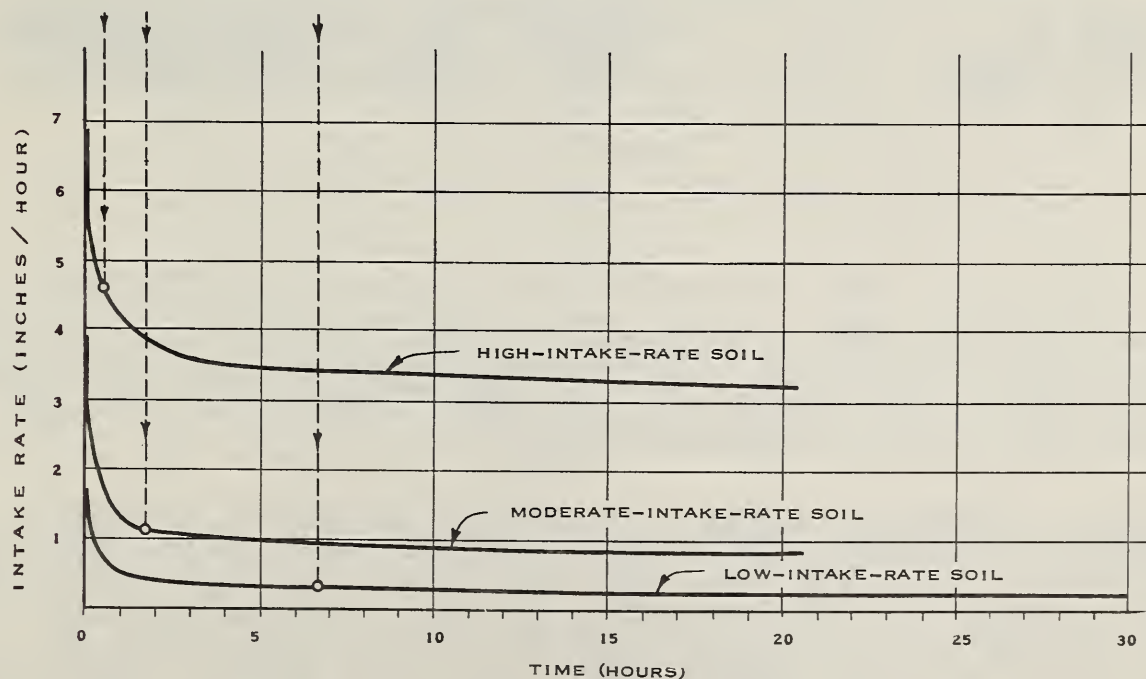


Figure 1-9.--Relation of intake rate to time for the three soils shown in figure 1-8. At end of the 3-inch application, the intake rate in the high-intake-rate soil has declined to 4.6 inches per hour, in the moderate-intake-rate soil to 1.2 inches per hour, and in the low-intake-rate soil to 0.3 inch per hour.

different for the three soils. In the high-intake-rate soil, the intake rate is still declining rapidly; in the low-intake-rate soil, the intake rate is nearly stable.

BASIC INTAKE RATE. Although the term "basic intake" (or "final intake") has been widely used, it has been only loosely defined. Generally, it has meant the nearly constant rate that develops after some time has elapsed from the start of irrigation. Thus, the low-intake-rate soil shown in figure 1-9 probably would be assigned a basic rate of about 0.3 inch per hour. Assigning a basic rate to a high-intake-rate soil is more difficult because usually irrigation ceases before anything approaching the basic rate has been reached. In the Soil Conservation Service, a change in intake rate of 10 percent or less in an hour has been considered unimportant. Hence, the basic rate is considered to be the point on the curve at which the change in rate is 10 percent. Since the significance of the terms basic rate and final rate often has been misunderstood, they are seldom used by SCS.

AVERAGE INTAKE RATE. The average intake rate, which has been used in some areas in designing surface-irrigation systems, is computed by dividing total intake by time. The average intake rate for the moderate-intake-rate soil in figure 1-9, for example, can be computed in the following way.

<u>Amount of intake in inches</u>	<u>Time in hours</u>	<u>Average intake rate in inches per hour</u>
1	1/3	3.0
3	1-3/4	1.7
6	4-1/2	1.3

The average intake rate for a given soil changes when the amount of intake changes, whereas the basic rate remains the same. Complete intake curves as expressed by intake families provide a much better tool and are now used in SCS for irrigation design.

INTAKE RELATIONSHIP FOR DESIGN. For sprinkler irrigation, the rate of application is planned to be no higher than the rate at which a soil can absorb water, and so the intake rate-time relationship (fig. 1-9) is the basis for design. It should be pointed out that soils that respond similarly when flooded may show widely different responses under the impact of droplets. The general shape of the curve, however, remains the same as that shown in figure 1-9 and indicates that for a given soil the maximum rate of application may be higher for light applications than for heavy applications. To be of value for sprinkler design, these curves must be developed by applying water in a manner similar to sprinkler application and for cover similar to the crop that is to be irrigated.

In surface methods of irrigation, the relation of total intake to time is the basis for system design. This curve (fig. 1-8) shows the length of time water must be applied to a given soil for a specified application amount. Such curves can be developed by following the procedures outlined under Methods of Determining Intake.

Intake Families

Each kind of soil has its own intake characteristics, but the differences between some soils are so minor that for all practical purposes several soils can be considered together. Eight groups, shown in figure 1-10, can be used to characterize intake. These groups, called intake families, have been assigned numbers such as 0.1, 0.3, and 0.5, which are merely designations that approximate the basic-rate values for soils in those families.

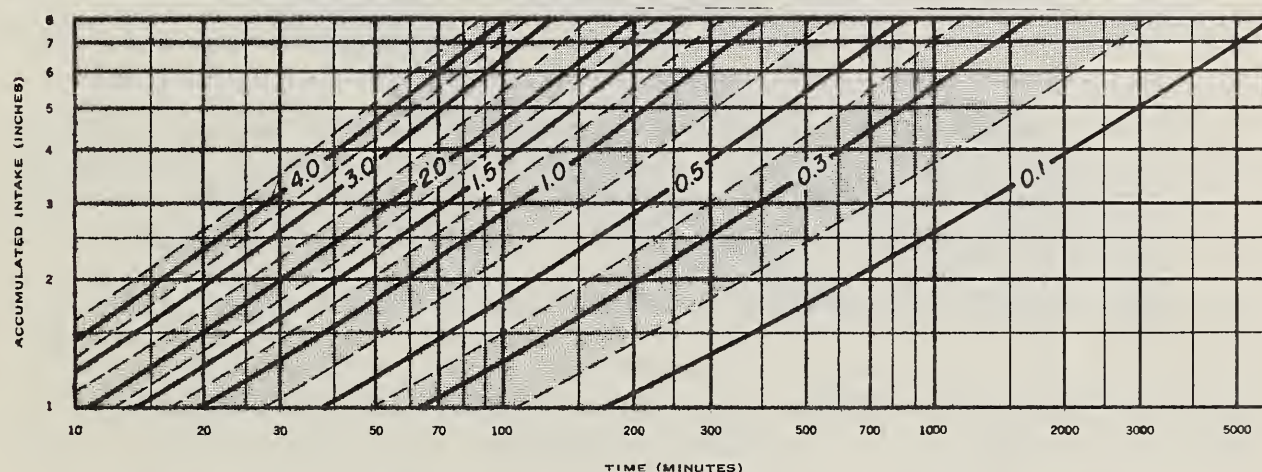


Figure 1-10.--Intake families for surface-irrigation design.

The intake families shown in figure 1-10 were developed by analyzing cylinder-infiltrometer data for a large number of sites. For most soils, curves developed from measured data closely parallel those shown in this figure. These typical curves apply only to soils that do not crack much on drying. They were plotted on a logarithmic scale to better represent values for short periods of time.

The families shown represent about equal increments in the change of recommended length-of-run for surface methods. Comparison of a series of intake measurements for a given soil with figure 1-10 will help to determine the correct intake curve to be used for design. Thus, the moderate-intake-rate soil shown in figure 1-8 may be considered to be in the 1.0-intake family because its values show that it has a very close resemblance to the 1.0 curve in figure 1-10.

Although the typical intake families shown in figure 1-10 were determined from test results applicable only to surface-flooding methods, it is logical to assume that the same general relationships hold for other surface-irrigation methods. Thus, soils that are in the same intake

family when irrigated by surface-flooding methods can be expected to be in the same family when irrigated by other surface methods such as furrows.

Figure 1-11 shows the intake characteristics measured by cylinder-infiltrometer tests for two soils. Each of these curves represents a single test of five cylinders each. Test A follows the typical curve very closely and indicates that this soil is in the 0.5 family. Test B does not follow the typical curve so closely, but the soil tested is well within the 2.0 family for a total intake of 2-1/2 to 8 inches. The normal irrigation application on this deep silt loam for the crops grown ranges from 3 to 6 inches. We can conclude, therefore, that for design purposes this soil is in the 2.0 family.

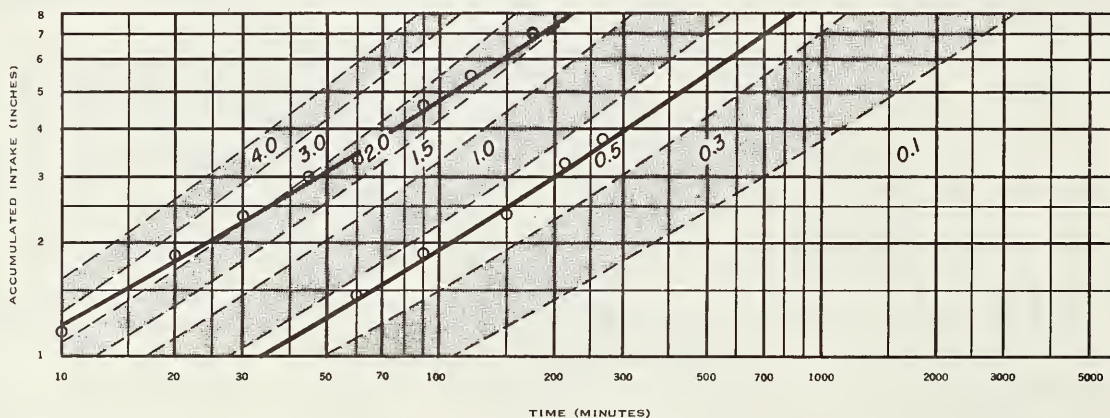


Figure 1-11.--Example of the classification of a soil in an intake family by test.

Figure 1-12 shows intake curves for two soils that crack. Here the water that enters the cracks is an appreciable amount of the total irrigation, and the intake rate is very slow after the first few minutes. Soils with these characteristics must be specially evaluated in designing a system.

Intake Variability

If a series of tests is made on the same field at different times under different conditions, the results may seem to place the soils in several intake families. Seldom, if ever, do all parts of a field or a soil type have the same intake rate since minor variations affect intake. The effect of any compaction caused by operating farm equipment over the field is particularly noticeable. Even the most uniform soil has some variation in physical properties, and no two soil samples give exactly the same test results.

In designing an irrigation system, therefore, the engineer must determine the intake rate that most nearly represents the usual condition and then provide facilities that permit changes in management that may be needed for other intake conditions. If this is done, irrigation efficiency will be highest when the actual field condition matches that used to design the system. Satisfactory efficiency can be had with little

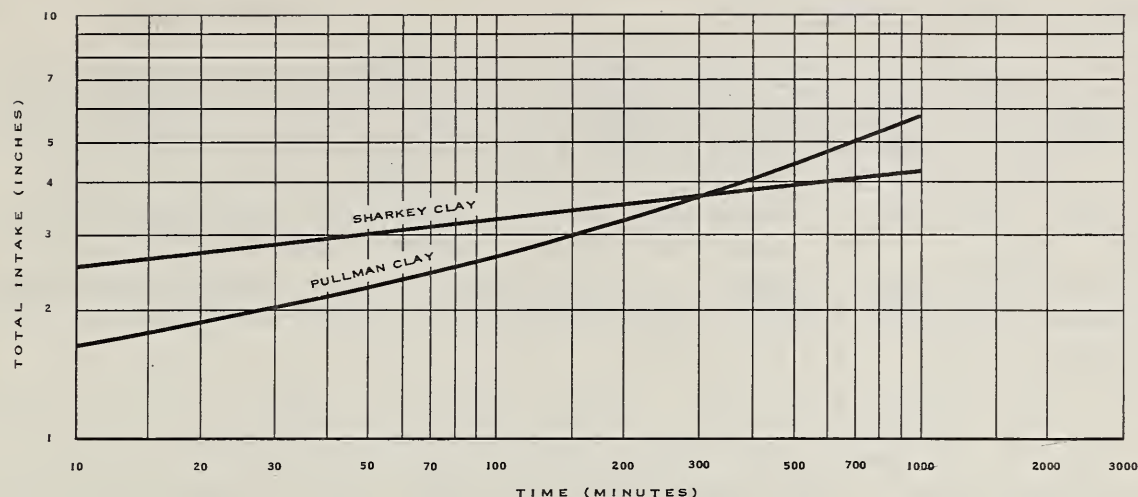


Figure 1-12.--Total intake and time relation for two soils that crack on drying.

change in procedure if the actual field condition is no more than one intake family different from that used for design. If there is more variation in intake, the stream size used may need to be adjusted to maintain acceptable irrigation efficiency with surface methods.

Figure 1-13 shows the amount of variation in test results for a group of deep, uniform, medium-textured soils in one State. Of the 286 sites tested, 26 percent are in the 0.3, 25 percent in the 0.5, and 16 percent in the 1 intake family. The midpoint is 0.5, and this is probably the logical design family for these soils. This particular grouping is based on texture alone. If other physical properties in addition to texture had been used to characterize these soils, this one group might have been broken up and there might be considerably less variation in any one group.

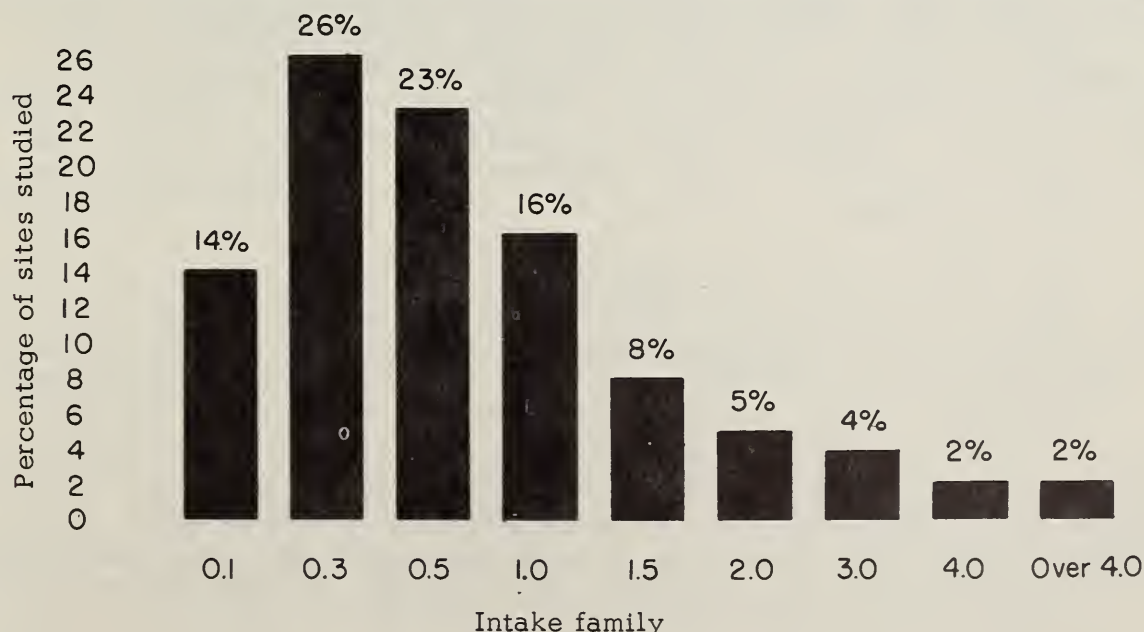


Figure 1-13.--Example of variation in intake characteristics and distribution in intake families for a group of medium-textured soils.

Methods of Determining Intake

Many of the present irrigation systems, both surface and sprinkler, are poorly suited to the soils and topography on which they are used. Often the intake rate was not known before a field was laid out and an irrigation system designed. In most areas where irrigation is now being developed, few data on intake rate are available. For successful irrigation, studies to determine the effective intake rate must be made in all irrigated areas in order to improve design criteria and operational techniques. Standard methods and procedures for these studies have been developed.

For sprinkler-irrigation design, a good way to determine the intake rate is to measure the water-application rate at selected points in the distribution pattern of operating sprinklers. Measurement should be delayed until near the end of a normal irrigation "set," at which time the intake rate of the soil is approaching the minimum value. To make the measurements, catch cans are placed at the points at which the application rate seems to equal the intake rate. The water collected in these cans in a given length of time is then measured to determine the application rate (maximum design intake rate) in inches per hour. Where a low application rate is commonly used, it may be necessary to change the nozzles on one or two sprinklers to obtain a rate adequate for one evaluation.

For furrow and corrugation methods of irrigation, intake characteristics usually are determined by inflow-outflow measurements. This procedure, which includes measuring the water entering the furrow, its rate of advance, and the outflow from the lower end, supplies a complete intake curve to use as a basis for design and operation.

For border and other controlled-flooding methods of irrigation, intake characteristics are often estimated by using cylinder infiltrometers. These intake curves are then used as a basis for designing irrigation systems and for management criteria. Inflow-outflow measurements, which include the rate of advance, time of recession, and depth of flow can also be used to determine intake characteristics for design and operation of border systems.

Plants

To design a successful irrigation system, the irrigation engineer must know the rooting characteristics of plants and how plants use moisture. Since a continuous supply of available moisture is necessary for good plant growth, the irrigation system for any given crop must be designed to supply the right amount of water during that crop's peak-use period. To determine the amount of soil moisture available to that crop, it is necessary to know from what depth of soil the plants get their moisture, or their moisture-extraction pattern, and how fast they use moisture.

ROOTING CHARACTERISTICS

The size of the soil reservoir that holds water available to a plant is determined mostly by that plant's rooting characteristics. The distribution of its roots determines its moisture-extraction pattern.

How Plants Get Their Moisture

Most plants have an enormous absorbing root surface. Near the growing tip of each root or rootlet, there are many root hairs in close contact with soil particles and with the air spaces from which roots get their oxygen. Through osmotic and other forces, root hairs extract moisture from the film of water that surrounds each soil particle.

Two phenomena seem to explain how a plant gets the enormous amount of water it takes in and transpires: (1) Capillary movement of water to plant roots and (2) growth of roots into moist soil.

As roots take up moisture, tension around the soil particles increases and water moves toward these points of plant absorption. How effective capillary movement is depends on how much water can be delivered to the soil around the roots and how fast it gets there. But since there is little root extension when the soil-moisture content is low, it is likely that near the wilting point any water that reaches plant roots must move to them.

During favorable growing periods, roots often elongate so rapidly that satisfactory moisture contacts can be maintained even when the soil-moisture content declines and without much help from capillary movement. Where a good root system has developed during favorable growing periods, a plant can draw its moisture supply from deeper soil layers. Thus if the roots in the upper part of the soil have depleted the moisture there to below the wilting point, plant needs can still be met provided roots have already grown into deeper layers that contain an adequate moisture supply.

Kinds of Root Systems

The kind of root system a plant develops is fixed by heredity. Each species has its own characteristic growth habit. Some plants have a tap root that penetrates deeply into soil under favorable conditions. Other plants are slow growing and develop shallow primary roots and many lateral roots.

Most of the roots of spinach and celery are in the surface foot of soil, and those of potatoes are within the upper 2 feet. Corn, cotton, and tomatoes permeate an open soil to a depth of 4 feet or more. Alfalfa and asparagus roots penetrate good soils to a depth of 8 to 10 feet or more. Cucumber roots extend laterally 5 or 6 feet in the plowed layer. Asparagus roots make little lateral spread in comparison with their depth.

Figure 1-14 shows root systems of various crops grown in deep, well-drained, irrigated soils in central United States.

Soil Effects on Root Development

Root penetration is seriously affected by a compacted layer in the soil; in many cultivated soils a compacted layer at plow depth confines crop roots to the upper 6 to 8 inches. Roots cannot penetrate a ledge or hard layer except through cracks. Thus in shallow soils, crop roots may be confined to a thin layer of soil regardless of their usual pattern. For crops growing in soils made up of layers of sandy material and clay loam, root development usually is much greater in the layers of clay loam than in those of sandy texture.

Since roots make almost no growth in soil that is depleted in moisture down to and below the permanent wilting point, a layer of dry soil below the surface can control depth of rooting. A high water table limits root growth, and a rising water table may kill roots that have previously grown below the new water level. Thus, saturation of the soil above the normal root-zone depth of a plant restricts root development. A deficiency of plant nutrients in the subsoil also limits the depth of root penetration.

Figure 1-15 illustrates the effect on root development of some of the limiting factors in soil.

Effects of Climate on Root Development

Irrigated soils in arid regions are usually coarser textured, permeable to a greater depth, and more deeply and better aerated and have a more fertile subsoil than irrigated soils in humid regions. Since most of these soils are deep and fertile enough to permit deep rooting, moisture and nutrients are available to crops in the deeper soil layers not much affected by evaporation.

At the beginning of the growing season, the upper part of many irrigated soils in humid areas is at field capacity and the lower part is saturated or nearly saturated as the result of winter and spring rains. This results in shallower root growth than in irrigated arid soils. In general, therefore, the soil-moisture reservoir is smaller in humid regions than in arid regions. Because of the large amount of moisture in the subsoil in spring, it usually is necessary to replace by irrigation only the moisture that crops have extracted from the upper part of the root zone. Thus, lighter irrigation applications are usually required.

Other climatic factors that affect root development are length of the growing season and temperatures in the growing season.

Moisture-Extraction Patterns

For most plants, the concentration of absorbing roots is greatest in the upper part of the root zone (usually in the top foot) and near the base

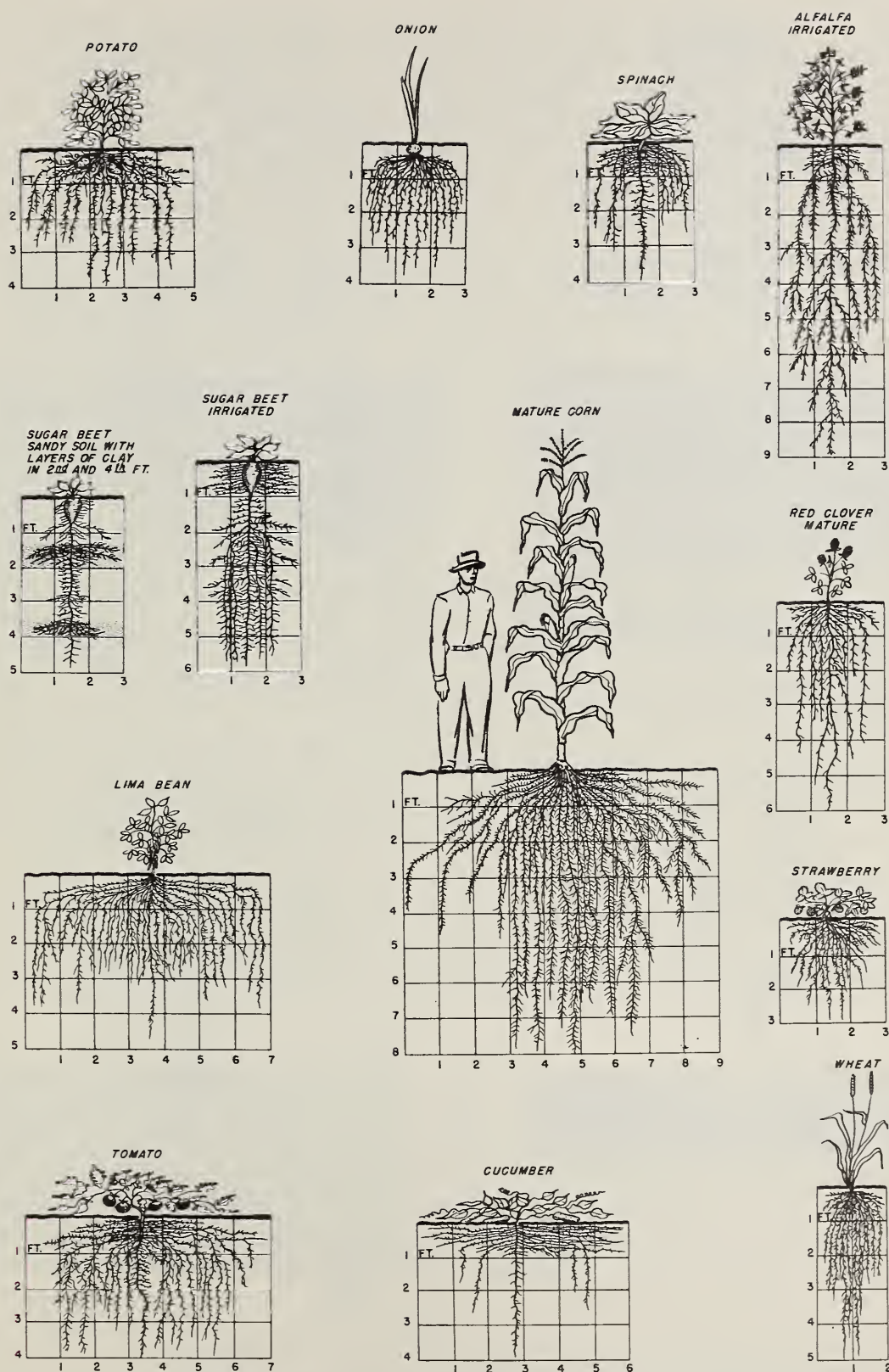


Figure 1-14.--Root systems of field and vegetable crops in deep irrigated soils of central United States.

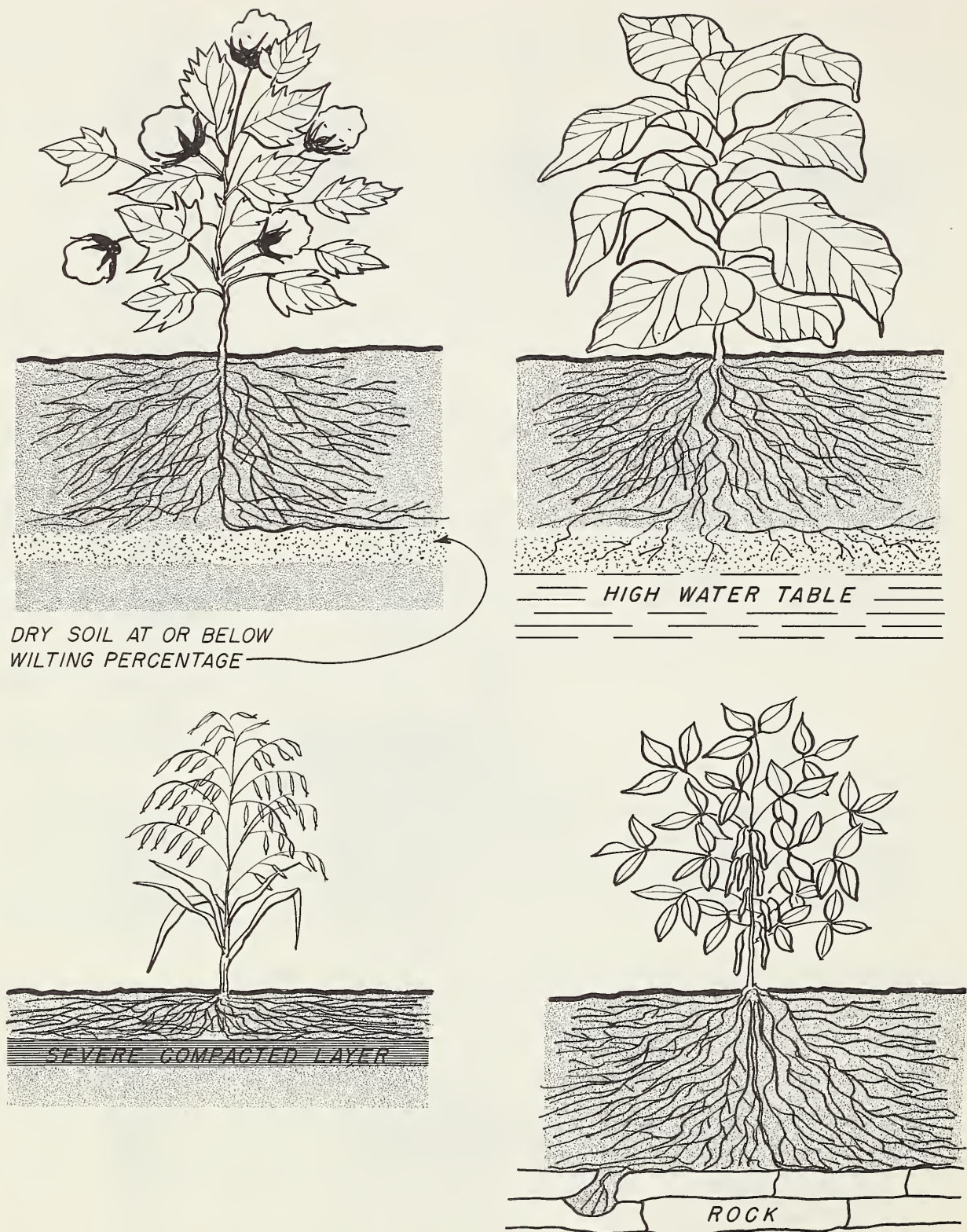


Figure 1-15.--Soil effects on root development.

of the plant. Extraction of water is most rapid in the zone of greatest root concentration and under the most favorable conditions of temperature and aeration. Since water also evaporates from the upper few inches of soil, moisture is withdrawn rapidly from the upper part of the soil. As the amount of moisture in this part of the root zone is diminished, soil-moisture tension increases. Plants then get moisture from lower parts of the root zone.

In uniform soils that are fully supplied with available moisture, plants use water rapidly from the upper part of the root zone and slowly from the extreme lower part. Basic moisture-extraction curves indicate that almost all plants growing in a uniform soil with an adequate supply of available moisture have similar moisture-extraction patterns. The usual extraction pattern (fig. 1-16) shows that about 40 percent of the extracted moisture comes from the upper quarter of the root zone, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the bottom quarter. Values for individual crops are within a range of ± 10 percent.

In nonuniform soils, the amount of moisture available for crop growth may be determined by the soil layer that has the lowest amount of available moisture. If the top layer of a soil has a low water-holding capacity, the available moisture is soon exhausted. If the moisture supply is not immediately replenished, plants can draw moisture only from lower levels at a less efficient rate and their growth is retarded. Any lower layer in the soil that has a low water-holding capacity also limits the total amount of moisture that plants can use. Some examples of limiting layers are shown in figure 1-17.

The usual extraction pattern for a given crop is changed by any barrier in the soil that restricts root development. Similarly, if the moisture level in the upper layers of the soil drops much below field capacity, a plant's extraction pattern differs greatly from its usual pattern (fig. 1-18).

Design Moisture-Extraction Depth

This is the soil depth used to determine irrigation-water requirements for design. It is the depth in which a high moisture level must be maintained for top production of agricultural crops. It is not necessarily the maximum root depth for any given plant, especially for plants that have a long tap root. For best results, it should be the depth from which most of the feeder roots of an average mature plant extract moisture.

Since root development for any one crop varies in different parts of the country because of soil and climatic differences, the design depth should be based on local moisture-extraction data for locally adapted crops. If two or more plant species with different rooting characteristics are to be grown together, the design depth should be that of the plant having the shallower root system.

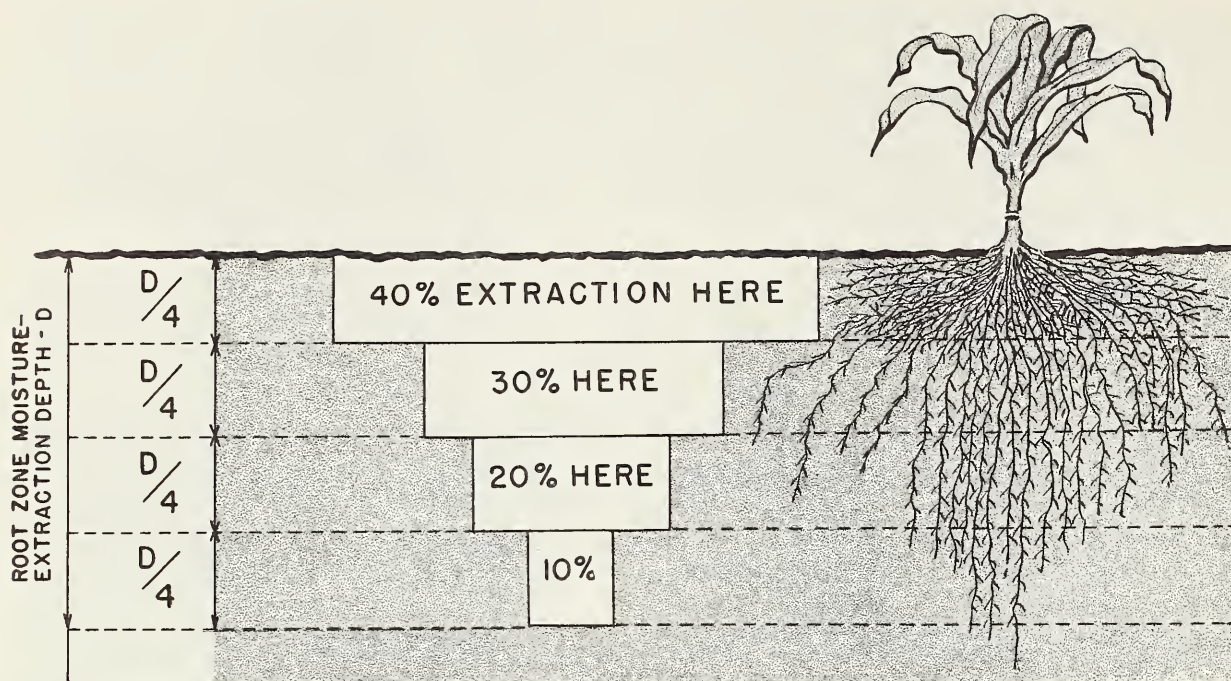


Figure 1-16.--Average moisture-extraction pattern of plants growing in a soil without restrictive layers and with an adequate supply of available moisture throughout the root zone.

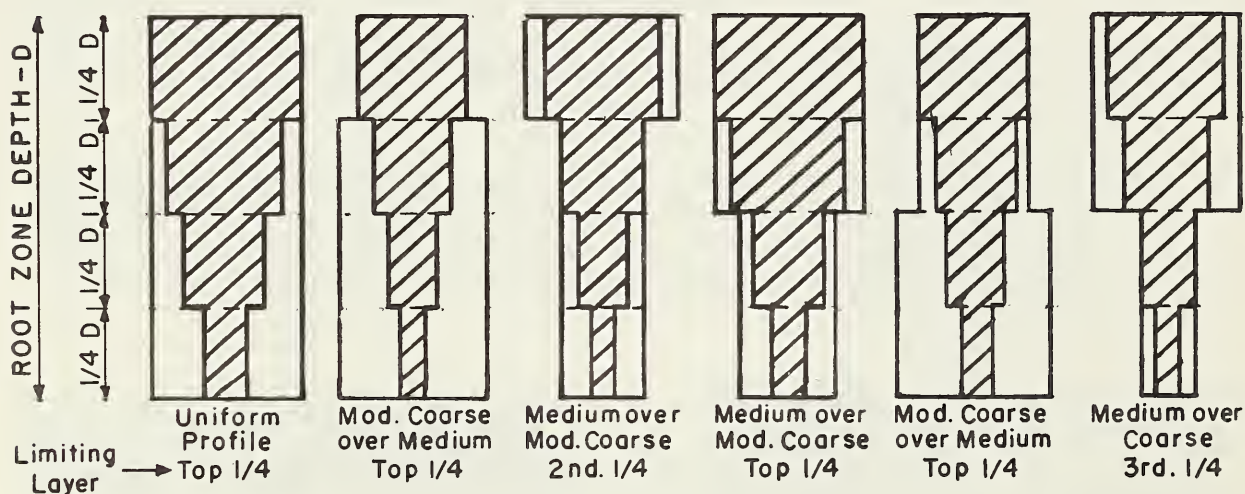


Figure 1-17.--Moisture-extraction patterns as determined by available-moisture content in various parts of soil profile. Width of each profile represents available moisture; gross area (height and width) of each profile represents total available moisture in profile; hatched area shows moisture-extraction pattern for each profile. (Redrawn from Shockley, Dale R. Capacity of Soil To Hold Moisture. Agr. Engin. 36(2): 109-112. 1955.)

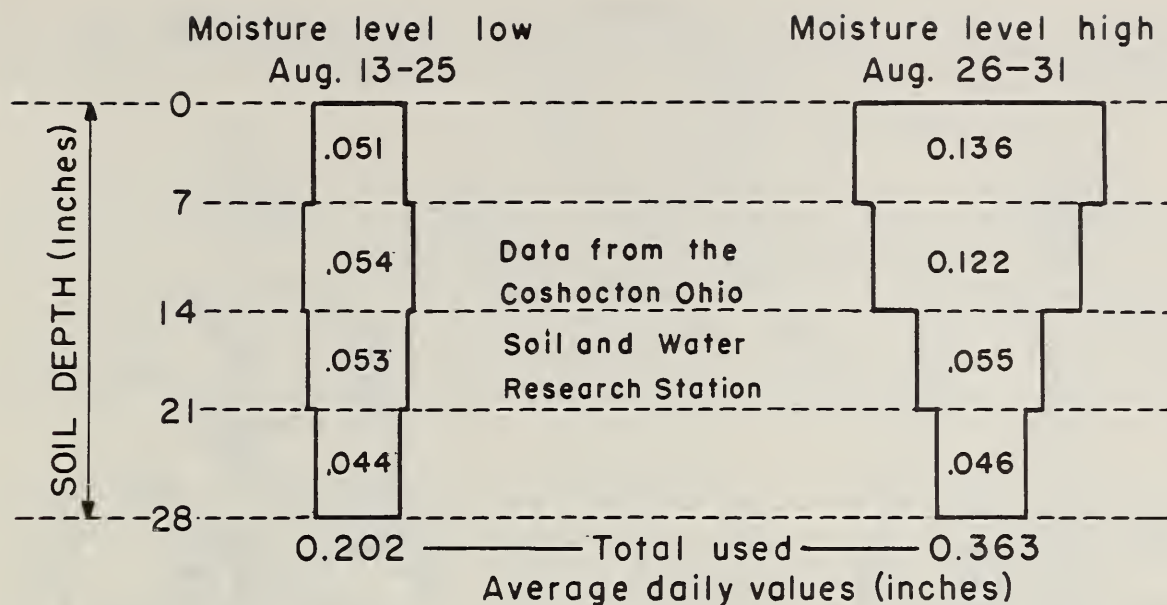


Figure 1-18.--Moisture-extraction patterns for a low and a high moisture level. (Redrawn from Harrold, L. L. Available Moisture for Crops. Agr. Engin. 35: 99-101. 1954.)

Table 1-4 gives examples of the design moisture-extraction depth for various crops and geographical areas for deep, medium-textured, moderately permeable soils.

CONSUMPTIVE USE

Consumptive use, often called evapotranspiration, includes water used by plants in transpiration and growth and that evaporated from the adjacent soil and from precipitation intercepted by plant foliage (fig. 1-19). It is expressed in acre-feet or acre-inches per acre or in depth in feet or inches.

Transpiration is the process by which water is removed from the soil by a plant, moved through the plant to the leaves, and lost to the atmosphere in vapor form. For irrigation, the moisture used in plant growth and that retained by the plant is included. Evaporation from the soil surface is not included in transpiration but is included in consumptive use.

Transpiration occurs mostly from the leaves of a plant, but a small part of the emitted moisture comes from the younger stems. It occurs mostly during the daylight hours, and only a small amount, possibly 5 to 10 percent, occurs during the night. The rate of transpiration is lowest just before sunrise and usually reaches a maximum shortly before noon. Transpiration accounts for a substantial part of the total consumptive use of a crop.

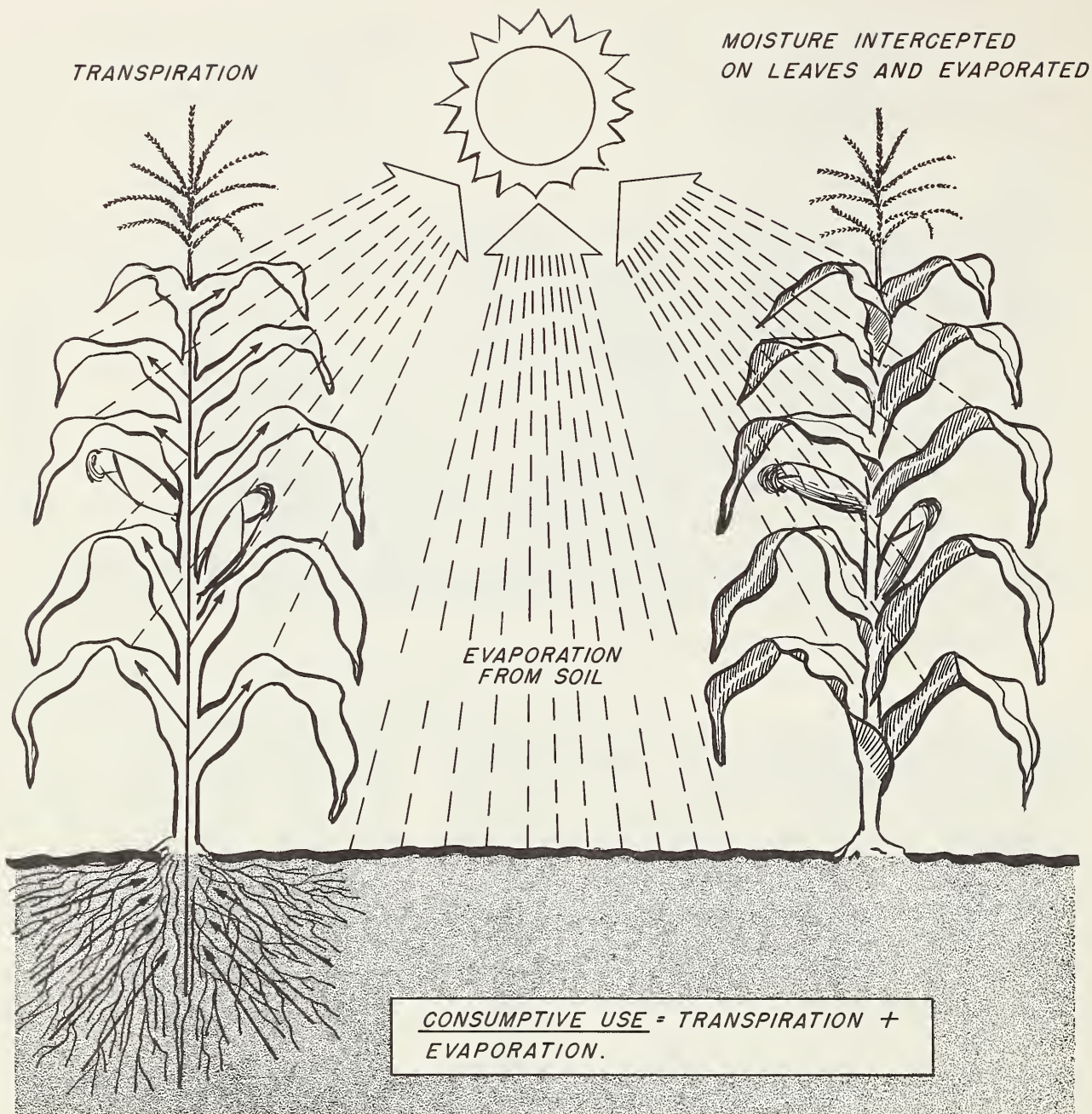


Figure 1-19.--Diagram of consumptive use.

Some of the factors that affect the rate of transpiration are moisture available in the soil, kind and density of plant growth, amount of sunshine, temperature, and soil fertility. In summer when exceedingly hot winds blow over a field, transpiration may take place more rapidly than moisture can be absorbed by plant roots even when the soil contains an ample supply of moisture. When this occurs, plants wilt. In some the foliage may be dried beyond recovery.

Evaporation is the diffusion of water as a vapor from a surface into the atmosphere. Factors that affect the rate of evaporation are the nature

of the evaporating surface and differences in vapor pressure as determined by temperature, wind, and atmospheric pressure. In determining consumptive use, evaporation includes both evaporation from the ground surface and evaporation of the water intercepted by vegetation.

In irrigated fields, frequent shallow irrigations tend to increase water loss by soil evaporation. If less frequent heavy irrigations are used, the soil surface is wetted less often and water penetrates to a greater depth in the soil. Consequently, a larger part of the irrigation water is available for crop use. In fields of hay, pasture, or other close-growing crops, evaporation from the soil is reduced not only because the plants transpire a large proportion of the soil moisture but also because they shade the soil.

Soil texture affects evaporation. Evaporation is higher in soils in which capillary movement of water to the surface is rapid. Conversely, evaporation is not so high in soils through which water percolates freely. Losses of water from soil by evaporation vary greatly not only in different parts of the United States but also at different times and under different conditions in the same part. Appreciable wind movement, high temperature, and low humidity generally result in a high rate of evaporation if there is enough moisture at the soil surface.

After an irrigation, evaporation from the surface of the soil is high so long as the topsoil remains saturated; the rate is about the same as that from a water surface of the same temperature. Depletion of the moisture in the topsoil rapidly reduces the rate of evaporation. The evaporation rate between irrigations depends somewhat on tillage operations, cultivation, and mulching as well as on soil texture, weather conditions, kind of crop, stage of crop growth, and the method, frequency, and depth of irrigation. As plants develop and provide increasingly more shade, the amount of evaporation is progressively reduced.

Daily Consumptive Use

Daily consumptive use, that in a 24-hour period, varies as the factors that influence evaporation and transpiration vary. Consumptive use is low at the start of the growing season, increases as plant foliage develops and days become longer and warmer, generally reaches a peak during the fruiting period, and then rapidly declines to the end of a crop's growing season. From the time seed is planted until plants emerge, soil-moisture loss is by evaporation. As plants emerge, transpiration begins and increases in amount as they develop. After the plants die, transpiration ceases and further soil-moisture loss is by evaporation. If all the physical and climatic conditions remain the same, daily consumptive use drops in hay and pasture fields immediately after cutting or grazing because of the reduction in transpiration. If the field is irrigated immediately after cutting, however, there is no reduction in daily consumptive use and the rate may even increase because of high evaporation.

Figure 1-20 shows how daily consumptive use varies throughout the year for corn and meadow at Coshocton, Ohio.

Seasonal Consumptive Use

The total amount of water used in evaporation and transpiration by a crop during its growing season is called seasonal consumptive use. It is expressed usually as acre-inches per acre or as depth in inches but sometimes as acre-feet per acre or depth in feet. Seasonal consumptive-use values are needed to evaluate and determine seasonal irrigation-water supplies.

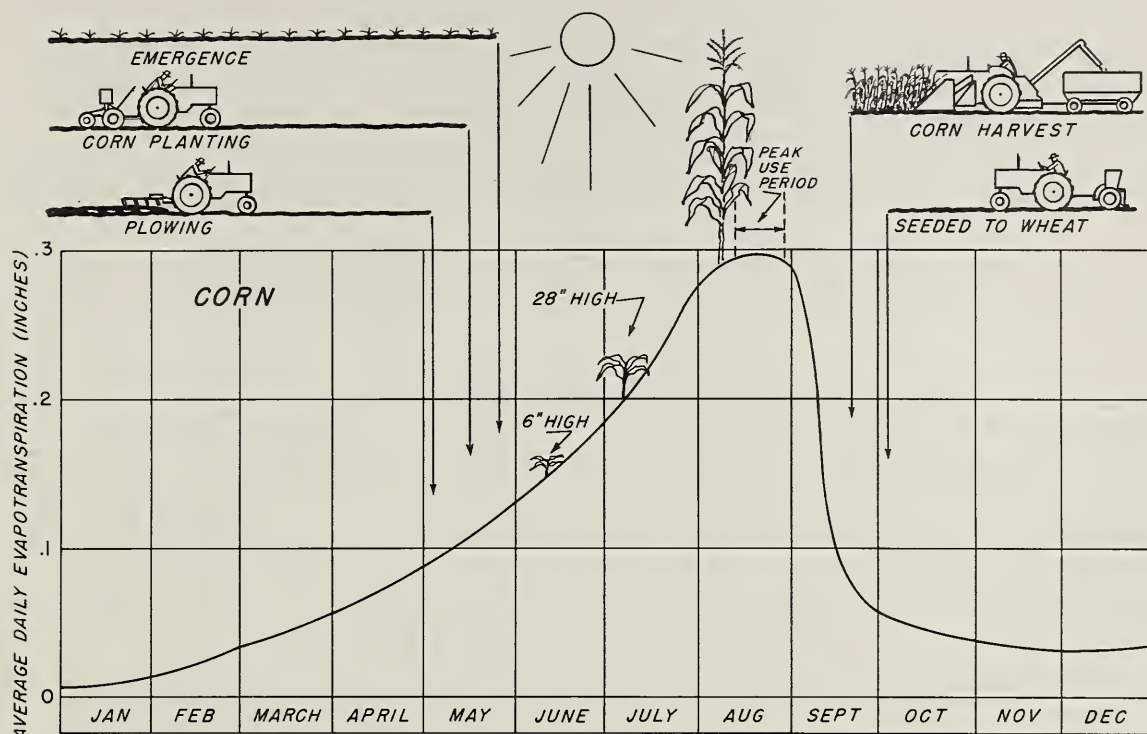
Peak-Period Consumptive Use

The average daily water-use rate during the 6 to 10 days of the highest consumptive use of the season is called the peak-period use rate and is the design rate to be used in planning an irrigation system. The peak-use period generally occurs when the crop is starting to produce its harvest, vegetation is most abundant, and temperatures are high.

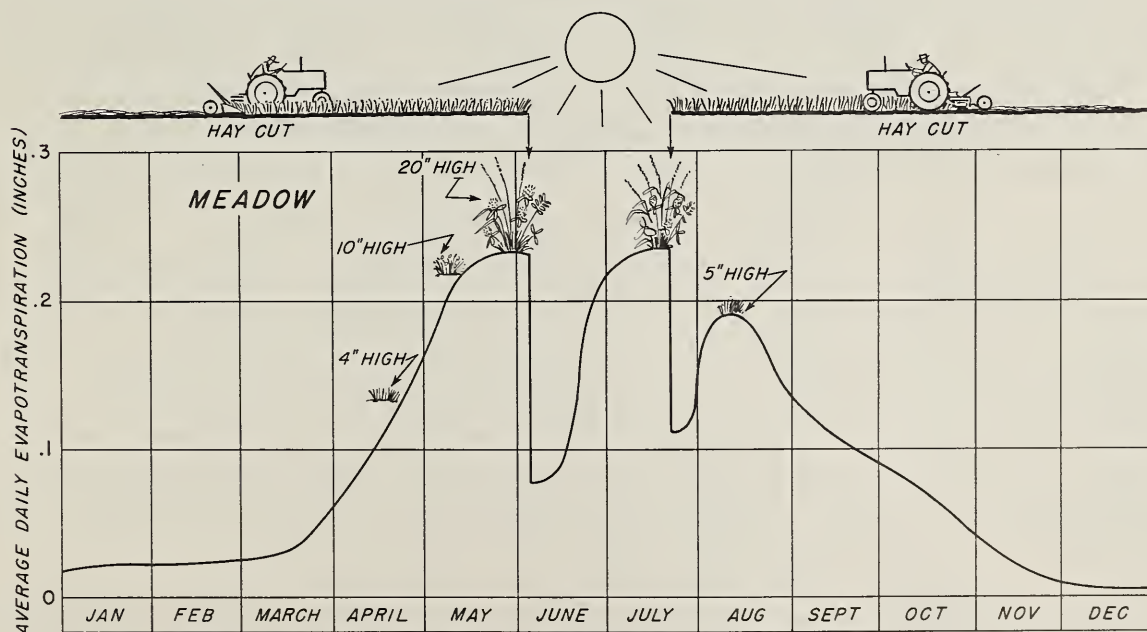
Since the average consumptive-use rate is higher for a very short peak-use period (2 or 3 days) than for a longer peak-use period, the design rate varies with the amount of water that can be used from the root zone (the normal depth of water application per irrigation). In shallow soils, in soils with a low water-holding capacity, or for plants with shallow root systems, the depth to which water is applied is shallow and irrigation frequency during the peak-use period ranges from 3 to 6 days. The peak-use period for plants with a moderately deep root system growing in deep soils with a good water-holding capacity may range from 8 to 15 days. The average use rate for these short periods is considerably higher than the average rate for the month of greatest moisture use and is generally less than the peak daily-use rate. Deep-rooted crops, such as alfalfa, growing in deep soils have a large reservoir to draw on, and the irrigation interval may range from 3 weeks to 1 month; the design rate is equal to or possibly slightly higher than the average rate in the month of greatest moisture use.

The peak-use period for various crops in a given area may occur at different times in the growing season. Early-maturing crops have their peak-use period in late spring or early summer and late-maturing crops, in late summer or early fall. Knowing when these peaks occur is important in working out a cropping plan in which the peak-use periods are staggered, thus reducing the total capacity requirement of the irrigation system. If two or more crops are grown in the same field, such as a permanent cover crop in an orchard or grain with a new alfalfa seeding, the peak moisture requirement of the crop or crop combination that uses more water must be met.

Table 1-4 gives some examples of the peak-period design rate for various crops grown on deep, medium-textured, moderately permeable soils in selected areas.



CONSUMPTIVE USE FOR YEAR 1953 WITH CORN, FOLLOWED BY WINTER WHEAT UNDER IRRIGATION ON LYSIMETER Y102 C AT THE SOIL AND WATER CONSERVATION RESEARCH STATION, COSHOCTON, OHIO.



CONSUMPTIVE USE FOR YEAR 1955 WITH IRRIGATED FIRST YEAR MEADOW OF ALFALFA, RED CLOVER, TIMOTHY ON LYSIMETER Y102 C AT THE SOIL AND WATER CONSERVATION RESEARCH STATION, COSHOCTON, OHIO.

Figure 1-20.--Average daily consumptive use for irrigated corn and meadow at Coshocton, Ohio. (From Harrold, L. L., and Dreibelbis, F. R. Evaluation of Agricultural Hydrology by Monolith Lysimeters, 1944-55. U.S. Dept. Agr. Tech. Bul. 1179, 166 pp. 1958.)

Table 1-4.--Design moisture-extraction depth and peak-period consumptive-use rate for various crops grown on deep, medium-textured, moderately permeable soils¹

Crop	Washington (Columbia Basin)		California (San Joaquin Valley)		Texas (Southern High Plains)		Arkansas (Mississippi bottoms)		Nebraska (eastern part)		Colorado (western part)	
	Depth	Use rate	Depth	Use rate	Depth	Use rate	Depth	Use rate	Depth	Use rate	Depth	Use rate
	In.	In. per day	In.	In. per day	In.	In. per day	In.	In. per day	In.	In. per day	In.	In. per day
Corn.....	42	0.27	60	0.26	72	0.30	30	0.23	72	0.28	48	0.23
Alfalfa.....	60	.25	72	.25	72	.30	42	.24	96	.27	72	.23
Pasture.....	24	.29	24	.32	³ 42 ⁴ 72	.25 .30	³ 36 ⁴ 36	.13 .22	48	.29	36	.23
Grain.....	48	.21	48	.17	72	.15	24	.15	48	.26	36	.22
Sugar beets....	36	.26	72	.22					48	.26	48	.20
Cotton.....			72	.22	72	.25	36	.18				
Potatoes.....	24	.29	48	.24					36	.26	36	.22
Deciduous orchards.....			96	.21							72	.18
Citrus orchards.			72	.19								
Grapes.....			72	.18								
Annual legumes..					48	.18	18	.28				
Soybeans.....							36	.19	60	.27		
Shallow truck...												
Medium truck....							⁵ 18 ⁶ 18	.20 .12				
Deep truck.....												
Tomatoes.....											36	.22
Tobacco.....												
Rice.....							24	.17				

Crop	Wisconsin (State)		Indiana (State)		Piedmont Plateau ²		Virginia (Coastal Plain)		New York (State)	
	Depth	Use rate	Depth	Use rate	Depth	Use rate	Depth	Use rate	Depth	Use rate
	In.	In. per day	In.	In. per day	In.	In. per day	In.	In. per day	In.	In. per day
Corn.....	24	0.30	24	0.30	24	0.22	24	0.18	24	0.20
Alfalfa.....	36	.30	36	.30	36	.25	36	.22	30	.20
Pasture.....	24	.20	30	.30	24	.25	20	.22		
Grain.....	18	.25			24	.16				
Sugar beets....	18	.25								
Cotton.....					24	.21				
Potatoes.....	18	.20	12	.25	24	.18	18	.18	18	.18
Deciduous orchards.....	36	.30			36	.25	36	.22	36	.20
Citrus orchards.										
Grapes.....			24	.25	30	.20				
Annual legumes..										
Soybeans.....	18	.25	24	.30	24	.18				
Shallow truck....	12	.20	9	.20	12	.14			12	.18
Medium truck.....	18	.20	12	.20	18	.14	18	.16	18	.18
Deep truck.....	24	.20	18	.20	24	.18			24	.18
Tomatoes.....	18	.20	18	.20	24	.21	24	.18	24	.18
Tobacco.....			24	.25	18	.18	18	.17		
Rice.....										

¹ From current irrigation guides.² Parts of Georgia, Alabama, North Carolina, and South Carolina.³ Cool-season pasture.⁴ Warm-season pasture.⁵ Summer.⁶ Fall.

Irrigation-Water Requirements

The net irrigation-water requirement is the amount of water exclusive of precipitation required for crop production. In other words, it is the amount of irrigation water that must be stored in the root zone to meet the consumptive-use requirement of a crop. The gross irrigation-water requirement includes the net requirement and also any losses incurred in distributing and applying water and in operating the system.

Effect of Soil-Moisture Level on Crop Growth and Yield

Crops vary in the soil-moisture level that must be maintained for optimum yields and quality. Most plants are more efficient in taking up water if the soil-moisture level is high. As the moisture level drops, soil-moisture tension increases and eventually plants cannot extract enough moisture for maximum growth. Plants begin to wilt, and growth is retarded or completely stopped. When the moisture level is again restored by irrigation, some crops continue to grow and show little or no permanent damage. Other crops, however, are permanently damaged, and if the moisture level is at or near the wilting point for a considerable period, complete crop failure is possible. Even if a crop recovers without serious damage, the growing time lost affects possible maximum yields.

Moisture-level studies by Mech at Prosser, Washington, show that depletion of moisture to the wilting point markedly depressed yields of corn. A moisture deficit for 1 or 2 days during the tasseling or pollination period reduced yields by as much as 22 percent. A moisture deficit for 6 or 8 days reduced yields by 50 percent. For production of high yields, moisture sufficient to prevent any wilting throughout the growing season is essential.

If sugar beets are allowed to reach the wilting point, yields are materially reduced. Since cotton uses varying amounts of water efficiently, a high moisture level is not so important as for some other crops. Cotton should not be allowed to be at stress, however, or yields will be reduced. The trend in cotton irrigation is to maintain a high moisture level during the latter part of the growing season. Tobacco is easily damaged by excess moisture, particularly in the early growth period when the moisture level should be fairly low. But a higher moisture level is required during the later growth period.

Early short-season truck crops benefit from a high moisture level. Indications are that other truck crops, such as onions and potatoes, also produce higher yields of better quality at a relatively high moisture level. Research in New York State at Cornell University showed an increase for onions of more than 140 bushels between moisture levels of 25 and 50 percent. For potatoes, the increase was about 80 bushels per acre.

To avoid the prolonged application that is required for a normal full irrigation, soils with a very low intake rate sometimes are irrigated when the moisture level is relatively high. These soils, on which water must be ponded for more than 12 hours or must be run in furrows for more than 48 hours to complete a normal irrigation, usually should be irrigated when the required application is equivalent to the amount the soil can absorb in this time.

Critical Periods

For most crops there are critical periods in the growing season when a high moisture level must be maintained for high yields. If there is enough moisture for germination and for the development of an adequate stand, the critical period almost always occurs in the latter part of the season when the crop is approaching harvest. The critical period for a number of commonly irrigated crops is shown in the following list.

Potatoes.....	Blossom to harvest.
Melons.....	Blossom to harvest.
Sweet corn.....	Tasseling through silking.
Tobacco.....	Knee-high to blossom.
Cotton.....	First bloom through boll-maturing stage.
Strawberries.....	Fruit development to ripening.
Field corn.....	Tasseling through silking.
Sugar beets.....	3 to 4 weeks after emergence.
Small grain.....	Boot to heading stage.
Pasture.....	After grazing.
Alfalfa.....	Start of flowering and after cutting.
Orchard.....	Fruit development.

Moisture Levels For Irrigation

It is not practical and probably not desirable to maintain the same soil-moisture level throughout the growing season. The objective of irrigation is to eliminate the limitation to crop production from lack of moisture. This can be done by providing at all times within the root zone of a given crop a supply of moisture at sufficiently low tension to be readily available.

The most desirable moisture level has not been determined quantitatively for all crops. Some crops require a relatively high moisture level for crop quality and high yields, i.e., between field capacity and a lower limit well above the wilting point. Thus, a high moisture level might mean that the moisture in the root zone is between the total amount that can be held by the soil (field capacity) and possibly 65 percent of the amount that can be held. The moisture level for irrigation would then be 65 percent. A high moisture level has been variously described by different authorities. Some consider a 30-percent level high, and others do not consider anything less than a 70- or 80-percent level high. For most crops, a low moisture level is generally considered to be 20 to 30 percent.

Some authorities feel that this whole concept is wrong. They think that the moisture level to be maintained should be based on predetermined soil-moisture-tension values at specified points in the root zone rather than on a minimum percentage of available moisture.

This difference in concept is illustrated by figure 1-21, which shows moisture-release curves for the three soils previously shown in figure 1-4. In this figure moisture content is expressed as a percentage of available moisture rather than as a percentage by weight. Field capacity is 100 percent of available moisture and the permanent wilting point is 0 percent (15 atmospheres). Tension at any moisture level is different for the three soils. At the 50-percent level, for example, moisture tension for the clay is 4.5 atmospheres; for the loam, 2 atmospheres; and for the sand, 0.75 atmosphere.

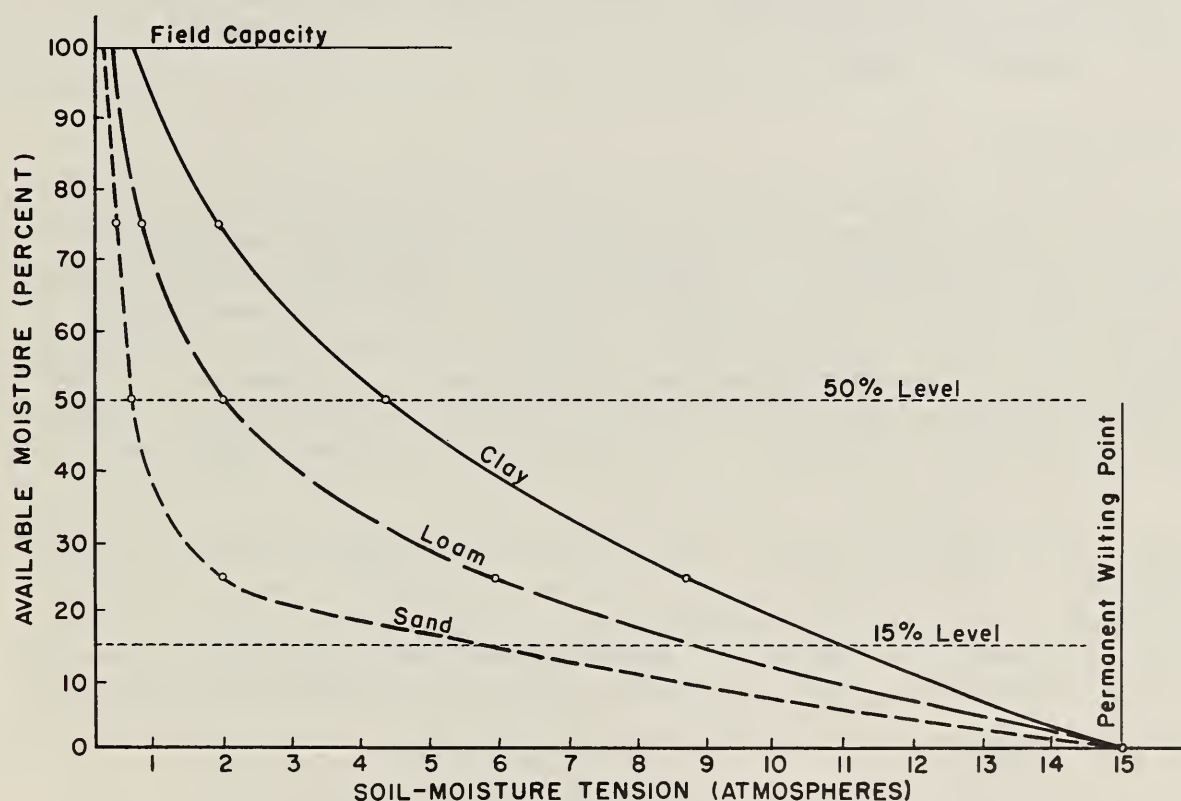


Figure 1-21.--Moisture-release curves for three soils. (From Thorne, M. D., and Raney, W. A. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6, 14 pp. 1956.)

It has been pointed out that moisture is more readily available to plants at low soil-moisture tension or near field capacity. Since tension values are so different in the three soils, it is possible that crop response would be different if the soils were irrigated when available moisture drops to the 50-percent level. But if these soils are irrigated when soil-moisture tension reaches 2 atmospheres, more comparable but not necessarily identical responses in yield may be

expected. At a tension of 2 atmospheres, the available-moisture content in the clay is 75 percent; in the loam, 50 percent; and in the sand, 25 percent.

Regardless of whether irrigation is specified by soil-moisture tension or by percentage of available moisture, a constant value cannot be used for all crops on all soils and be expected to provide uniform results. Different crops grown on various soils must be evaluated. It must be remembered also that many fields cannot be irrigated from one set or be covered in 1 day. In many places, several days are required to irrigate a field. The economic feasibility of covering a field in a given time and maintaining an adequate moisture level in the last part of the field to be irrigated must also be considered in determining the moisture level at which irrigation is to be started. The cost in labor and equipment required to maintain a high moisture level in the soil must be carefully balanced against any possible effects on crop yield, crop quality, and market price.

ARID-AREA LEVELS

In the arid and semiarid regions of the Western States, where nearly all the moisture for crop growth is supplied by irrigation, experience indicates the desirability of maintaining a minimum soil-moisture level of about 50 percent for most crops. Irrigation water is then applied when the soil-moisture level drops to about 50 percent. If the soil is brought up to field capacity at each irrigation, this provides a moisture level between field capacity and 50 percent at all times. A few crops, however, are benefited by maintaining a somewhat higher moisture level.

In these low-rainfall regions, irrigations are cyclic. After the first irrigations in the season, a pattern of soil-moisture levels is established across a field that coincides with the various irrigation "sets" required to cover the field. In later irrigations, each part of the field receives water when it reaches a specified minimum moisture level.

HUMID-AREA LEVELS

In humid areas, the problem is somewhat different from that in arid areas. Since precipitation in the growing season generally contributes materially to the soil moisture required for crop growth, irrigation is not continuous throughout the season. To make maximum use of rainfall during the growing season, research and experience indicate that irrigation can be scheduled by permitting the average moisture level of a field to range between a high point somewhat below field capacity and a low point somewhat above the wilting point.

The moisture level at which to start irrigation must be determined from a practical standpoint as well as from the requirements for optimum crop production. In humid areas, irrigation generally is an additional farm chore that must be fitted into the ordinary farm work. An irrigator

generally is reluctant to start irrigation at a high moisture level because the soil does not seem dry enough to warrant the trouble and labor of adding water when it may rain in a few days. Available research data on moisture and crop yields show that for most crops it is usually most practical to start irrigation when the available moisture in the root zone is 55 to 60 percent of capacity. This allows time to complete an irrigation before the last area to receive water becomes too dry. For some high-value crops on some soils that show great response to a high-moisture level, it may be economical to start irrigation when the level is 65 to 70 percent.

The lower limit of moisture depletion is an important determination in humid areas. Plants cannot extract the required amount of moisture when the available-moisture level approaches the wilting point because soil-moisture tension is high. Research shows a marked reduction in yield for nearly all crops if the moisture in the root zone falls to much less than 20 percent of the total amount of available water. On some soils, some crops are affected at the 35 to 50 percent level.

The critical moisture level varies with the soil as well as with the crop. Figure 1-21 shows that at a moisture level of 15 percent the soil-moisture tension for the sand is 5.8 atmospheres; for the loam, 8.7; and for the clay, 10.7. On the basis of tension, the moisture in the sand is more readily available than that in the clay. The moisture content of the sand, however, is almost down to the wilting point as shown in table 1-5. To provide a safety factor in operating the irrigation system, therefore, the lower limit of moisture depletion in the sand should be higher than 15 percent for some crops. More energy is required for a plant to extract moisture from the clay at the 15-percent level than from the sand at that level. But more moisture is available, which provides a greater safety factor.

Table 1-5.--Moisture available between the 15-percent level and the permanent wilting point for the three soils shown in figure 1-21

Soil	Moisture content at--			Differ- ence
	15-percent level		Permanent wilting point (15 atmospheres)	
	Soil-moisture tension	Amount		
	<u>Atmospheres</u>	<u>Percent by weight</u>	<u>Percent by weight</u>	<u>Percent</u>
Sand.....	5.8	5.3	4.8	0.5
Loam.....	8.7	10.0	11.3	1.3
Clay.....	10.7	19.3	17.0	2.3

Thus to be sure that plants are not overstressed, the lower limit of moisture depletion will not be the same for any one crop growing on different soils in different locations. Research and experience indicate that a moisture level of between 15 and 20 percent of the total available water generally is a good lower limit to use for design purposes for most irrigated crops. Certain special crops on particular soils may require a higher level for optimum economic returns.

MOISTURE TO BE REPLACED AT EACH IRRIGATION

The correct amount of water must be applied when it is needed to insure efficient operation of an irrigation system and optimum returns from the investment in irrigation. If more water is applied than is needed to bring the moisture level up to field capacity, the additional amount is lost by deep percolation. Unless the extra water is needed for leaching or for temperature control, there is no benefit from the higher cost. On soils in which internal drainage is slow, the additional water may result in reduced yields. But if not enough water is supplied, crop yields are also reduced.

The amount of water to be replaced at each irrigation, therefore, depends on the amount of available moisture the soil can hold in the moisture-extraction depth used in designing the system and on the moisture level selected for the start of irrigation.

Net Water Application

The net amount of moisture to be replaced at each irrigation is the amount that the soil can hold between field capacity and the starting moisture level. If the starting moisture level is set at 60 percent, the crop can use as much as 40 percent of the available moisture in the root zone before it is time to apply irrigation water. It is then necessary to add an amount of water equal to 40 percent of the available moisture the soil can hold in order to bring the root zone up to field capacity. If, for example, a soil holds 8 inches available in the design moisture-extraction depth and if irrigation starts at the 60-percent level, the net amount that must be added to the soil at each irrigation is equal to 40 percent of 8 inches, or 3.2 inches.

Another method of estimating the net amount of moisture to be replaced was suggested by Dale R. Shockley. In this method, which is based on the usual moisture-extraction pattern of irrigated crops, the available moisture that can be held in the upper fourth of the root zone is taken as about 40 percent of the total amount of water that can be used by plants between irrigations. It is also the net amount that must be replaced by irrigation. This is a maximum figure, and Shockley suggests reducing the total available moisture so computed by 1 inch to provide a reasonable safety factor. Thus for most irrigated crops on uniform soils, the net amount of moisture to be replaced can be estimated in the following way.

1. Determine the available moisture that can be held in the upper fourth of the crop root zone in the soil to be irrigated.
2. Divide this amount by 0.40 and subtract 1 inch. This is the net amount of moisture to be replaced.

The net amount of moisture to be replaced usually is 40 to 50 percent of the total amount of available moisture in the root zone of soils that have a uniform moisture-holding capacity in all increments of depth.

For low-moisture-holding soils underlain by subsoils that have a higher moisture-holding capacity, the net amount of moisture to be replaced, as determined by this procedure, is a smaller percentage of the total amount of available moisture than that for uniform soils. But for high-moisture-holding soils underlain by subsoils that have a lower moisture-holding capacity in the second or third quarter (fig. 1-17), the percentage is larger.

The following example shows how to estimate the net amount of moisture to be replaced in nonuniform soils.

1. Assume a soil that has an available moisture holding capacity of 1.75 inches in the upper foot and of 2 inches in each of the second, third, fourth, and fifth feet of depth and assume a root zone depth of 5 feet.
2. Since one quarter of the root zone is 1.25 feet and the amount of available moisture in the upper quarter is 2.25 inches (1.75 plus $\frac{1}{4}$ of 2), the net amount of moisture to be replaced is 4.6 inches ($\frac{2.25}{0.40}$ minus 1).

Gross Water Application

The gross amount of water to be applied at each irrigation is the amount that must be applied to the surface to be sure enough water enters and is held in the soil to meet the net requirement for each irrigation. Regardless of the method used, no irrigation system is 100 percent efficient and not all the water applied during an irrigation enters and is held in the root zone.

Unavoidable losses are caused by unequal distribution of water over a field, by percolation below the root zone, and by waste at the ends of borders and furrows. In sprinkler irrigation, additional losses are caused by evaporation from the spray and by the retention of water on plant foliage.

For a given irrigation method, field efficiency varies with the skill used in planning, laying out, and operating the system; with climatic conditions; and with the physical properties of the soil. To be sure that the net amount of moisture to be replaced at each irrigation enters and is retained in the root zone, it is necessary to apply a larger amount of water to the soil surface to offset any losses. This gross

amount to be applied can be determined according to the following equation.

$$\text{Gross amount} = \frac{\text{Net amount to be replaced (net water application for design)}}{\text{Efficiency of system}}$$

Varying Applications

In humid areas, different amounts of water are applied during any given irrigation to provide a high moisture level in the entire field. In many places, it is not possible to irrigate an entire field in 1 day, and several days are required. This means that the moisture level at the end of the field opposite to that from which irrigation is started is well below the prescribed starting moisture level by the time water is applied to that end of the field and the moisture level in much of the field is below the prescribed starting level.

This lower moisture level is not important for crops that do not require a high moisture level for optimum yields. But yields of crops that benefit greatly by a sustained high moisture level will be reduced. For certain high-value crops, it may be advantageous to maintain a high moisture level over an entire field. This can be done by applying increasing amounts of water as irrigation progresses across a field. One method is to increase the application each day by an amount equal to the daily moisture-use rate of the crop. Some irrigators prefer to increase the amount for each one-third of the field. For example, if irrigation is started at the 60-percent moisture level and the minimum level is 20 percent, an amount of water equal to 40 percent of the total amount of available moisture is applied to the first one-third of the field. The amount is increased to 55 percent for the second third and to 70 percent for the last third of the field. If it is necessary to irrigate again immediately, the starting amount can be used throughout the second and each succeeding cycle since all parts of the field are then brought up to field capacity with each irrigation application.

When To Irrigate

IRRIGATION FREQUENCY

Irrigation frequency refers to the number of days between water applications or irrigations. It depends on the consumptive-use rate of a crop and on the amount of available moisture in the root zone (moisture-extraction depth) between field capacity and the starting moisture level for irrigation. It is a function of both soil and crop: for any given crop, open shallow soils must be irrigated more often than fine-textured deep soils; the moisture-use rate varies with the kind of crop and increases as the crop grows larger and the days become hotter.

Irrigation frequency in the growing season depends mostly on the stage of plant development. There must be plenty of water during germination and plant emergence for good stands. Then the crop must be irrigated

often with fewer and fewer days between irrigations until flowering time. During the maturing period, not so many irrigations are needed with more days between them. Usually no irrigation is needed during ripening.

The irrigation frequency to be used for design is the time (in days) between irrigations in the period of highest consumptive use of the crops grown. Since frequency depends on how long water added to the soil and held there lasts when a crop is transpiring at its maximum rate, the average moisture-use rate during this period is the rate to be used in designing and planning irrigation systems, as discussed earlier under Peak-Period Consumptive Use. For an irrigation system to be adequate for all the requirements of a crop, it must be large enough to supply the water necessary during this period.

$$\text{Design frequency} = \frac{\text{Net amount of moisture between field capacity and starting level}}{\text{Peak-period moisture-use rate of crop}} \quad \text{or} \quad \frac{\text{Net depth of application}}{\text{Peak-period use rate}}$$

IRRIGATION PERIOD

Irrigation period refers to the number of days that can be allowed for applying one irrigation to a given design area during the peak consumptive-use period of the crop being irrigated. It is the basis for capacity and equipment design.

Since the peak-use period is generally the critical time in the crop cycle and since a shortage of moisture during this period greatly affects yields, a system that cannot furnish water to an entire field or farm in the allowable number of days is not satisfactory. The irrigator sacrifices top yields for a smaller initial cost, and his net returns generally are lower over the life of the irrigation system.

For arid regions where irrigations are cyclic and the moisture level is maintained between field capacity and about 50 percent, irrigation period and irrigation frequency are identical.

In humid regions, irrigation period is not always the same as irrigation frequency because irrigations generally are not cyclic and application procedures are somewhat different from those in arid regions. When rainfall brings the entire field up to field capacity, soil moisture can be depleted to some predetermined percentage of that in the extraction depth before irrigation is started. The amount of moisture remaining in the soil then determines the amount of time that can be allowed for covering the field in one irrigation. If the starting level is set at some low percentage of the total amount of available moisture, the moisture remaining in the soil is already low and the time that can be allowed for covering the field before wilting occurs on the far side is

much less than it is when irrigation is started at a higher moisture level. For this reason, irrigation period may not be the same as irrigation frequency. In other words, the amount of available moisture in the soil between the starting moisture level and the lower limit of moisture depletion is the amount of water the crop has available for growth during the irrigation cycle. Thus,

$$\text{Irrigation period} = \frac{\text{Net amount of moisture in soil between start of irrigation and lower limit of moisture depletion}}{\text{Peak-period moisture-use rate of crop}}$$

In the following example, the total amount of available moisture in the extraction depth of a given soil is 6 inches, the crop to be irrigated has a peak-period use rate of 0.3 inch per day, and irrigation is to be started when moisture level is 50 percent and is to be finished when the moisture level at the far end of the field is 20 percent. The net amount to apply is

6 inches x 50 percent or 3 inches,

and the irrigation frequency is

$$\frac{3 \text{ inches}}{0.3 \text{ inch/day}} \text{ or } 10 \text{ days}$$

The moisture in the soil between the starting level and the lower limit of moisture depletion is

6 inches x (50 percent - 20 percent) or 1.8 inches,

and the irrigation period is

$$\frac{1.8 \text{ inches}}{0.3 \text{ inch/day}} \text{ or } 6 \text{ days.}$$

The irrigation system, therefore, must have the capacity and equipment for covering the entire field by one irrigation in 6 days. If 3 inches of water is applied during the irrigation, however, it is necessary to irrigate only every 10 days during the peak-use period.

In humid areas the procedure generally used to limit moisture depletion is to set moisture levels for the start and finish of an irrigation so that the difference between field capacity and the starting level is the same as that between the starting level and the finishing level, as shown in figure 1-22. With this procedure, irrigation period equals irrigation frequency.

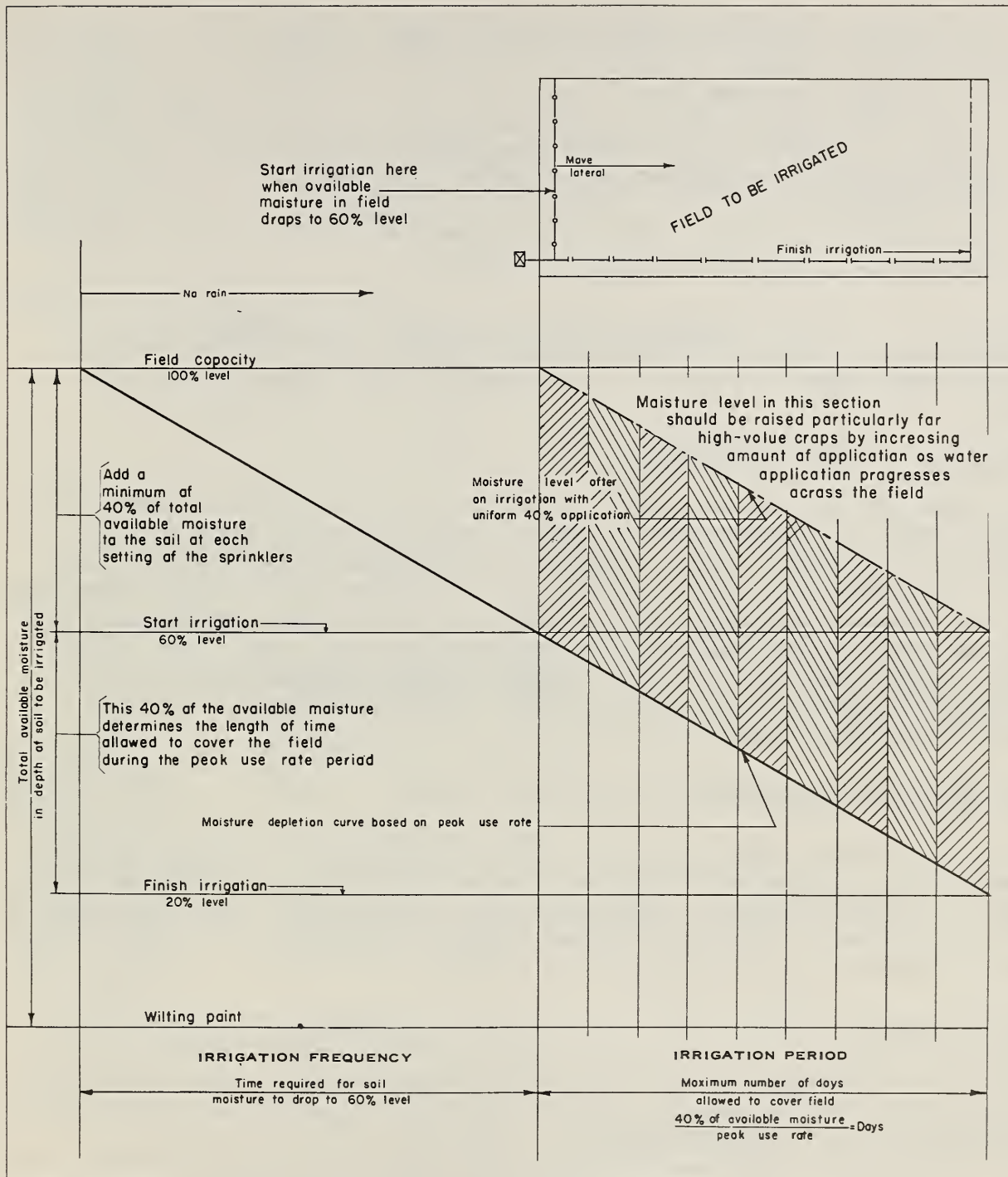


Figure 1-22.--Limiting soil-moisture depletion in humid areas.

An irrigation system designed to cover an area in approximately the time represented by the irrigation period requires a minimum system capacity and for a given water-application rate a minimum amount of irrigation equipment. The system may be designed for fewer days than specified by the irrigation period for one or more of the following reasons.

1. The irrigator desires some free time between irrigations.
2. Delivery or rotation schedules of irrigation enterprises.
3. Harvesting operations when it may be necessary to apply water during a relatively short period so that harvesting can be started. For hay it may be desirable to irrigate immediately after haying, and thus the area should be covered in a shorter time than the allowable irrigation period.
4. Special applications of water may be needed for crop quality, as for truck crops grown for canning or freezing.

Example 1-1 illustrates the principles of applying irrigation water in arid areas to a soil in which different layers have different water-holding capacities. Example 1-2 illustrates the principles in humid areas.

IRRIGATING BY CROP APPEARANCE

The appearance of the crop gives some indication of when to start irrigation. But crop appearance is often deceptive and its significance varies for different crops. Temporary wilting during the hottest part of the day sometimes indicates the need for water. But basing irrigation on crop appearance alone is dangerous, for some plants may not show any wilting until growth has been seriously retarded or some other injury has occurred. Generally if the irrigator waits for some sure sign of wilting, he may not be able to irrigate the entire field before the crop is seriously damaged.

IRRIGATING BY DETERMINING SOIL-MOISTURE LEVEL

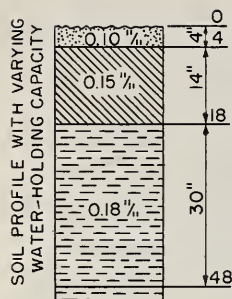
The best and most effective way of determining when to irrigate is to measure or to estimate the moisture level in the soil. By knowing the amount of moisture that is available, the irrigator who has knowledge of and experience with a particular crop on a particular soil can accurately determine when irrigation is needed.

Of the numerous methods that can be used to measure and estimate soil moisture, many are not suited to field use. But several methods are now being used by irrigators and others are being developed that show promise as methods of determining when to irrigate. Some of these methods are discussed in the following pages.

Location of Soil-Moisture Measurements

The location of any soil-moisture measurements is highly important. Selection of places that will give a good estimate of the moisture level over a field generally is a matter of knowing the soil, previous experience, and good judgement. Locating the places for examination is not so difficult in fields of the same kind of soil as in fields of different kinds.

It is generally recommended that one location be near the side of the field where irrigation is to be started as a reference point for



Example 1-1.--Sample problem illustrating the principles of irrigation-water application in arid areas.

Given:

Soil--Royal loamy fine sand
 Crop--sugar beets
 Design moisture-extraction depth--4 feet
 Design moisture level--minimum level controlled by available moisture in top quarter of root zone
 Efficiency--65 percent

Moisture to be replaced at each irrigation:

$$\text{Net amount} = \frac{\text{Total available moisture in top quarter of root zone}}{40 \text{ percent}} = 1$$

$$\text{One-fourth of root zone} = 48/4 = 12 \text{ inches}$$

$$\begin{aligned} \text{Available moisture--0 to 4 inch depth} &= 0.1 \times 4 = 0.4 \text{ inch} \\ 4 \text{ to 12 inch depth} &= 0.15 \times 8 = 1.2 \text{ inches} \\ \text{Total} &= 1.6 \text{ inches} \end{aligned}$$

$$\text{Net amount} = (1.6/40 \text{ percent}) - 1 = 3 \text{ inches}$$

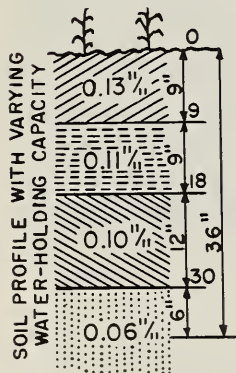
$$\text{Gross amount} = \frac{\text{Net amount}}{\text{Efficiency}} = \frac{3}{65 \text{ percent}} = 4.6 \text{ inches}$$

Irrigation frequency:

$$\text{Design consumptive-use rate for 3 inches extraction} = 0.27 \text{ inch per day}$$

$$\text{Design frequency} = \frac{\text{Moisture needed per irrigation}}{\text{Design consumptive-use rate}} = \frac{3}{0.27} = 11 \text{ days}$$

Example 1-2.--Sample problem illustrating the principles of irrigation-water application in humid areas.



Given:

Soil--O'Neil sandy loam
 Crop--corn
 Design moisture-use rate = 0.3 inch per day
 Moisture level to be controlled to a 3-foot depth
 Moisture level at start of irrigation--60 percent
 Lower limit of moisture depletion--20 percent
 Efficiency--70 percent

Moisture to be replaced at each irrigation:

$$\text{Net amount} = \text{Total available moisture in 3 feet} \times (100 \text{ percent} - 60 \text{ percent})$$

$$\begin{aligned} \text{Available moisture--} &\begin{cases} 0 \text{ to } 9 \text{ inch depth} = 0.13 \times 9 = 1.17 \text{ inches} \\ 9 \text{ to } 18 \text{ inch depth} = 0.11 \times 9 = 0.99 \text{ inch} \\ 18 \text{ to } 30 \text{ inch depth} = 0.10 \times 12 = 1.20 \text{ inches} \\ 30 \text{ to } 36 \text{ inch depth} = 0.06 \times 6 = 0.36 \text{ inch} \end{cases} \\ &\text{Total} = 3.72 \text{ inches} \end{aligned}$$

$$\text{Net amount} = 3.72 \times 40 \text{ percent} = 1.48 \text{ inches (use 1.5)}$$

$$\text{Gross amount} = \frac{\text{Net amount}}{\text{Efficiency}} = \frac{1.5}{70 \text{ percent}} = 2.15 \text{ inches}$$

Design frequency (how often to irrigate when crop is using maximum amount of moisture from the soil; also length of time allowed to irrigate the field--irrigation period):

$$\frac{\text{Net amount of moisture between start of irrigation and lower limit of depletion}}{\text{Peak-period moisture-use rate}} = \frac{(60 \text{ percent} - 20 \text{ percent}) \times 3.72}{0.3} = \frac{1.5}{0.3} = 5 \text{ days}$$

starting the irrigation cycle. At least one location should be at the opposite end of the field to determine if the field is being covered fast enough to maintain an adequate moisture level there. Measurements should be made at other locations as indicated by any critical condition in the soil, such as an area that dries out first or stays wet longest. It is good practice to have at least two measurement stations in each critical area and possibly two or three stations in areas that are typical of most of the field. An adequate system of moisture measurement provides the irrigator with enough data to manage his system so that the moisture level is controlled over the entire field. This kind of information serves as a guide in varying both the amount and the frequency of irrigation for different parts of the field or for different periods in the growing season.

For row crops, measurements should be made in the row or near the plants. In sprinkler irrigation, the measuring stations should be between the sprinkler heads and 10 to 15 feet away from the lateral. For trees, measurements generally are made 4 to 6 feet from the trunk but inside the drip line.

Measurements should be made in that part of the soil from which plant roots extract their moisture and according to the moisture-extraction pattern of the particular crop. One measurement should be made in the upper quarter of the root zone and one or two more measurements, at lower levels. If the maximum moisture-extraction depth for a given crop is 24 inches, for example, measurements probably should be made at about 6, 12, and 18 inches. To predict when to irrigate during the early stages of root development, the 6-inch measurement is all that is needed for most crops. As the root system reaches maturity, measurements from all three locations are needed for a clear picture of the moisture level throughout the moisture-extraction zone. Generally, the practice is to average the measurements from the three depths.

Reading and Recording Measurements

Measurements may need to be taken twice a week in spring and fall and daily during hot weather and the critical periods for the crop grown. The irrigator may be able to reduce the frequency of readings after he has become thoroughly familiar with the pattern of moisture depletion. After he gains experience, he should be able to determine from each day's reading what the conditions will be several days hence, so that he can complete an irrigation cycle before the crops irrigated at the end of the cycle show signs of stress. To accurately predict moisture levels, measurements must be taken and recorded regularly, regardless of the time of year or the stage of crop growth. Comparison of yearly records that are tied to crop yields helps the irrigator to improve his management of the irrigation system.

Soil-Sampling Method

Soil samples are taken from the desired depth at several locations for each soil type. They are weighed, dried in an oven, and then weighed

again. The difference in weight is the amount of moisture in the soil, which can be converted to inches of water remaining in the soil (p. 1-16).

Although this method gives good results, it is not used generally on farms. Its accuracy depends on the number of samples taken and on the skill used in mixing and handling the samples. It requires using facilities not ordinarily owned by farmers and much time and labor. It is used principally in experimental work and is a standard against which other methods of moisture determination can be compared.

Measuring Instruments

Various instruments for measuring soil moisture are available commercially. These instruments may not give such accurate results as the soil sampling and drying procedure, but they are being improved. If the instruments are well located and if the irrigator reads them consistently and interprets the results according to his knowledge of both crop and soil, he can closely predict the time to irrigate.

The instruments now available are of two general types: tensiometers and electrical-conductivity measuring devices.

TENSIOMETERS. Tensiometers (fig. 1-23) work on the principle that a partial vacuum is created in a closed chamber when water moves out through a porous ceramic tip to the surrounding soil. Tension is measured by a water manometer, a mercury manometer, or a vacuum gage. The scales are generally calibrated in either hundredths of an atmosphere or in centimeters of water. Tensiometers that utilize a mercury manometer are usually preferred as research tools because they afford great precision. Because of their simplicity, tensiometers equipped with Bourdon vacuum gages are better suited to practical use and to irrigation control.

After the cup is placed in the soil at the desired depth, the instrument must be filled with water. Water moves through the porous cup until the water in the cup and the water in the soil reach equilibrium. Any increase in tension that occurs as the soil dries causes the vacuum-gage reading, which can be read above ground, to increase. Conversely, an increase in soil-water content reduces tension and lowers the gage reading. The tensiometer continues to record fluctuations in soil-water content unless the tension exceeds 0.85 atmosphere, at which point air enters the system and the instrument ceases to function. After an irrigation or rain, the instrument must again be filled with water before it can operate.

Some experience is required to use a tensiometer. If air enters the unit through any leaks at the rubber connections, measurements are not reliable. Air leaks can result from faulty cups. They may occur also at the contact points of the setscrews used to secure the porous cup to the metal support. Some manufacturers provide a test pump that can be used to test the gage and to remove air from the instrument.

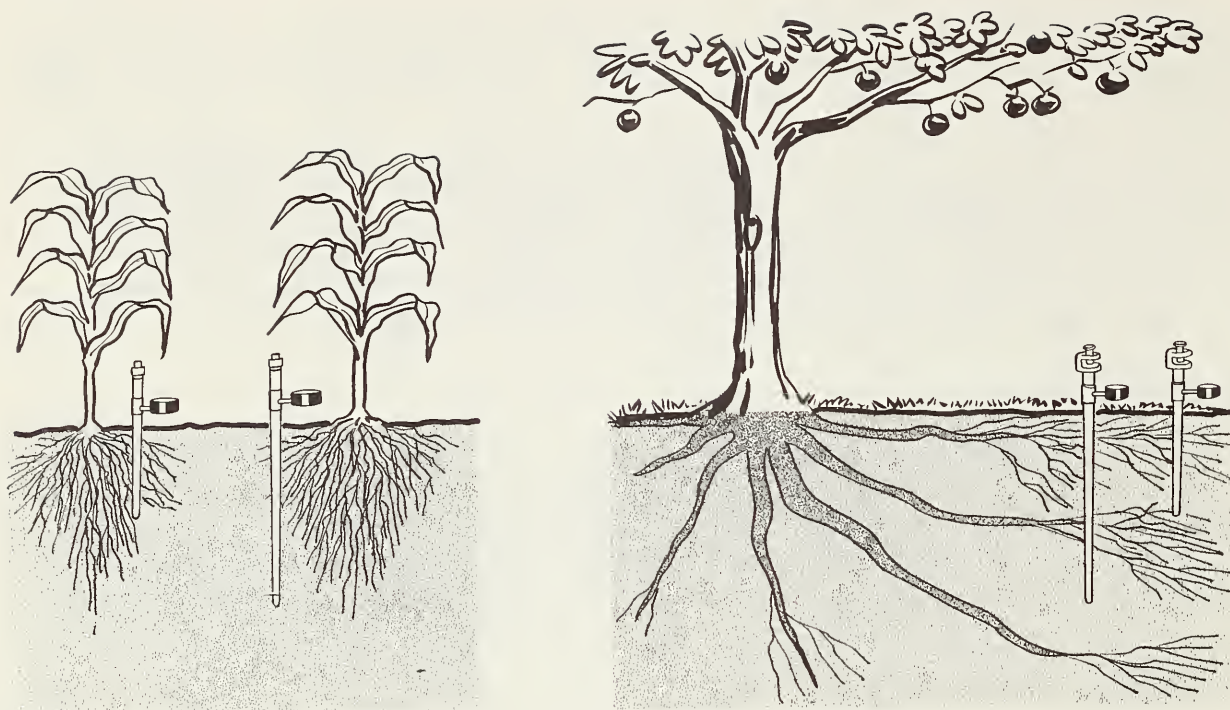


Figure 1-23.--Tensiometers used to measure soil moisture.

Tensiometer readings reflect soil-moisture tension only; that is, they indicate the relative wetness of the soil surrounding the porous tip. They do not provide direct information on the amount of water held in the soil. Tension measurements are useful in deciding when to irrigate, but they do not indicate how much water should be applied. A special moisture-characteristic curve for the particular soil is needed to convert moisture-tension measurements into available-moisture percentages. Typical curves for three sample soils are shown in figure 1-21 (p. 1-43).

Tensiometers do not satisfactorily measure the entire range of available moisture in all soil types. But they probably are the best field instruments to use to determine moisture conditions in the wet range. They are best suited to use in sandy soils since in these soils a large part of the moisture available to plants is held at a tension of less than 1 atmosphere. Tensiometers are less well suited to use in fine-textured soils in which only a small part of the available moisture is held at a tension of less than 1 atmosphere.

ELECTRICAL-RESISTANCE INSTRUMENTS. These instruments (fig. 1-24) use the principle that a change in moisture content produces a change in some electrical property of the soil or of an instrument in the soil. They consist of two electrodes permanently mounted in conductivity units, usually blocks of plaster of paris, nylon, fiber glass, gypsum, or combinations of these materials. Electrodes in the blocks are attached by wires to a resistance or conductance meter that measures changes in electrical resistance in the blocks. When the units are buried in the soil, they become almost a part of the soil and respond to changes in soil-moisture content. Since the amount of moisture in the

blocks determines electrical resistance, measurement of any change in resistance is an indirect measure of soil moisture if the block is calibrated for a particular soil.

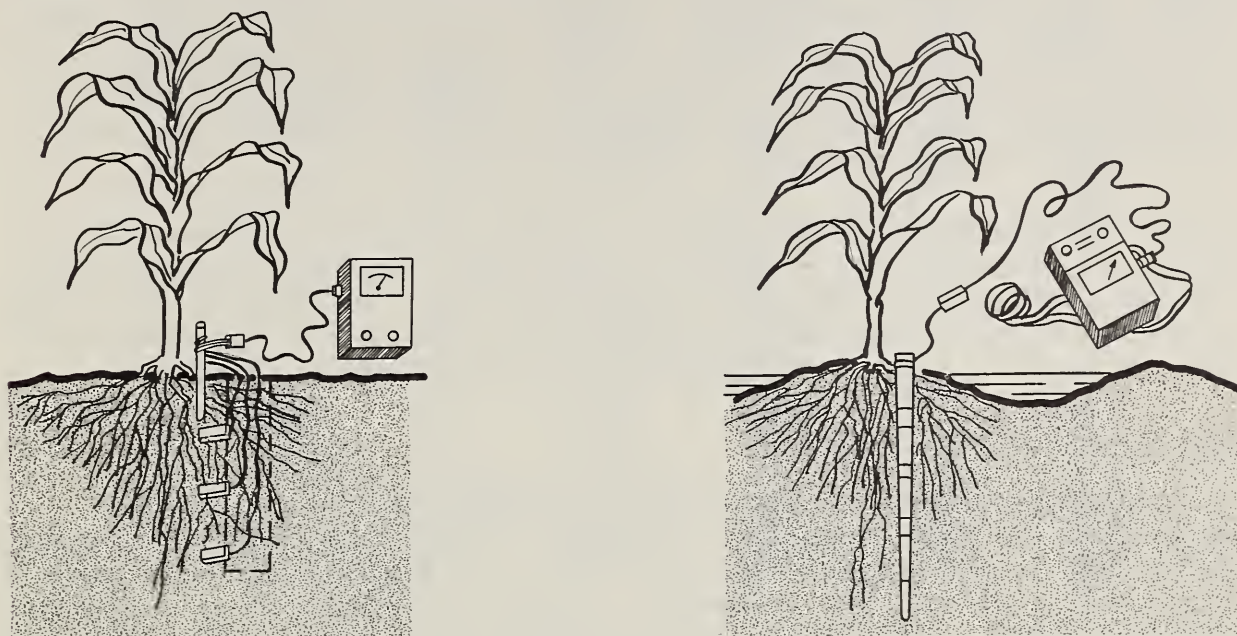


Figure 1-24.--Electrical-resistance soil-moisture meters.

Nylon and fiber-glass units are more sensitive in the higher ranges of soil moisture than plaster of paris blocks, but often their contact with soil that is alternately wet and dry is not very good. Nylon units are most sensitive at a tension of less than 2 atmospheres. Plaster of paris blocks function most effectively at a tension between 1 and 15 atmospheres, and fiber-glass units operate satisfactorily over the entire range of available moisture. A combination of fiber glass and plaster of paris provides sensitivity in both the wet and dry range and provides good contact between the soil and the unit.

Electrical-resistance instruments are sensitive to salts in the soil; fiber-glass units are more sensitive than plaster of paris. Their readings are also affected by concentrations of fertilizer. Where fertilizer is spread in bands, the unit should be placed well to one side of the bands. Temperature also affects readings in all units but much less than other sources of variation. In some units calibration drift has caused changes of as much as 1 atmosphere of tension in a single season. The magnitude of a change depends on the number of drying intervals and the number of days between each. Readings also vary with soil type. Since the same reading may indicate different amounts of available moisture for different soil textures, the instrument must be calibrated for the soil in which it is to be used.

If readings are to be representative of an area, the blocks must be properly installed. Individual blocks must be placed in a hole, which disturbs the soil. If the soil is not replaced in the hole at the same

density and in the same way as in the rest of the profile, the root-development and moisture pattern may not be representative. A good method is to force the block into undisturbed soil along the sides of the hole dug for placement of the blocks (fig. 1-24). In one type, the blocks are cast in a tapered stake. A tapered hole, the same size as the stake, is bored into the ground with a special auger. The stake is saturated with water and then pushed into the hole so that close contact is made between the stake and the soil.

Most of the commercial instruments give good indications of moisture content if they are used according to the manufacturer's instructions. For good results, however, the blocks need to be calibrated in the field for each job. Experience and careful interpretation of instrument readings are needed to get a good estimate of soil-moisture conditions.

Feel and Appearance Method

How soil samples taken in the field from appropriate locations and depths feel and look gives some indication of moisture content. A shovel can be used to get samples, but for some soils a soil auger or a sampling tube is better. The appearance and feel of a handful of soil that has been squeezed very firmly can be compared with descriptions in a guide of estimated available-moisture content for different soil textures and conditions. Table 1-6 is a guide that has been used for some time.

A slightly different and probably simpler guide was developed by John L. Merriam. In this guide (table 1-7) moisture deficiency can be read directly in inches per foot. The description at the top of each textural column is of the soil at field capacity. The description at the bottom of each column is of the soil at the wilting point. Descriptions of intermediate conditions of soil-moisture deficiency are opposite the corresponding numerical values of inches of water per foot of soil. Table 1-7 is for a specific group of soils, and it may not apply to many other groups. Descriptions for other soils may be somewhat different. Probably the best practice is to prepare a chart for a given area and for specific soils and then to furnish each irrigator with a chart that describes only the soils to be irrigated on his farm. These special charts should be developed by using laboratory methods to determine the soil-moisture deficiency that corresponds to each feel and appearance condition.

Although gaging moisture conditions by feel and appearance is not the most accurate method, with experience and judgement the irrigator should be able to estimate the moisture level within 10 to 15 percent. This method is one of the cheapest, but it requires a lot of work to get soil samples.

Table 1-6.--Practical interpretation chart of soil moisture for various soil textures and conditions

Available moisture in soil	Feel or appearance of soil			
	Coarse-textured soils	Moderately coarse textured soils	Medium-textured soils	Fine and very fine textured soils
0 percent----	Dry, loose, and single-grained; flows through fingers.	Dry and loose; flows through fingers.	Powdery dry; in some places slightly crusted but breaks down easily into powder.	Hard, baked, and cracked; has loose crumbs on surface in some places.
50 percent or less.	Appears to be dry; does not form a ball under pressure. ¹	Appears to be dry; does not form a ball under pressure. ¹	Somewhat crumbly but holds together under pressure.	Somewhat pliable; balls under pressure. ¹
50 to 75 percent.	Appears to be dry; does not form a ball under pressure. ¹	Balls under pressure but seldom holds together.	Forms a ball under pressure; somewhat plastic; slicks slightly under pressure.	Forms a ball; ribbons out between thumb and forefinger.
75 percent to field capacity.	Sticks together slightly; may form a very weak ball under pressure.	Forms weak ball that breaks easily; does not slick.	Forms ball; very pliable; slicks readily if relatively high in clay.	Ribbons out between fingers easily; has a slick feeling.
At field capacity (100 percent).	On squeezing, no free water appears on soil but wet outline of ball is left on hand.	Same as for coarse-textured soils at field capacity.	Same as for coarse-textured soils at field capacity.	Same as for coarse-textured soils at field capacity.
Above field capacity.	Free water appears when soil is bounced in hand.	Free water is released with kneading.	Free water can be squeezed out.	Puddles; free water forms on surface.

¹ Ball is formed by squeezing a handful of soil very firmly.

Table 1-7.--Soil moisture and appearance relationship chart¹

Moisture deficiency, in./ft.	SOIL TEXTURE CLASSIFICATION				Moisture deficiency, in./ft.
	Coarse (loamy sand)	Light (sandy loam)	Medium (loam)	Fine (clay loam)	
	(field capacity)	(field capacity)	(field capacity)	(field capacity)	
0.0	Leaves wet outline on hand when squeezed.	Appears very dark, leaves wet outline on hand; makes a short ribbon.	Appears very dark; leaves a wet outline on hand; will ribbon out about one inch.	Appears very dark; leaves slight moisture on hand when squeezed; will ribbon out about two inches.	0.0
0.2	Appears moist; makes a weak ball.				0.2
0.4	Appears slightly moist. Sticks together slightly.	Quite dark color; makes a hard ball.	Dark color; forms a plastic ball; slicks when rubbed.	Dark color; will slick and ribbon easily.	0.4
0.6	Very dry, loose; flows through fingers. (wilting point)	Fairly dark color, makes a good ball.	Quite dark, forms a hard ball.	Quite dark, will make a thick ribbon; may slick when rubbed.	0.6
0.8		Slightly dark color, makes a weak ball.	Fairly dark, forms a good ball.	Fairly dark, makes a good ball.	0.8
1.0		Lightly colored by moisture will not ball.			1.0
1.2		Very slight color due to moisture. (wilting point)	Slightly dark, forms a weak ball.	Will ball, small clods will flatten out rather than crumble.	1.2
1.4			Lightly colored; small clods crumble fairly easily.	Slightly dark, clods crumble.	1.4
1.6					1.6
1.8			Slight color due to moisture, small clods are hard. (wilting point)		1.8
2.0				Some darkness due to unavailable moisture, clods are hard, cracked, (wilting point)	2.0

THIS chart indicates approximate relationship between field capacity and wilting point. For more accurate information, the soil must be checked by drying samples of it. The descriptions at the top of each textural column correspond to the condition of zero soil-moisture deficiency, i.e., field capacity. Those descriptions at the bottom of a column describe a soil having the maximum deficiency, i.e., at wilting point. The soil-moisture deficiency at this condition is numerically equal to the available moisture range of the soil. Intermediate soil-moisture deficiency descriptions occur opposite corresponding numerical values of inches of water per foot of depth at which the soil is deficient. This chart describes a specific group of soils and though it has been found to have general application, it may not apply to many other groups. Where this is the case, new descriptions will need to be prepared corresponding to particular soil-moisture deficiency, feel, and appearance relationships.

¹ From Merriam, J. L. Field Method of Approximating Soil Moisture For Irrigation. Amer. Soc. Agr. Engin. Trans. 3(1): 31-32. 1960.

Moisture-Accounting Method

The moisture-accounting method is a bookkeeping procedure developed and used to some extent in the East to estimate soil-moisture content by using climatological data. It is based on two important principles:

1. If there is an adequate supply of available moisture in the soil, the consumptive-use (evapotranspiration) rate for any given crop depends primarily on climatological conditions.
2. If the moisture content of a soil is known for any given time, the moisture content at any later time can be computed by adding water gains (effective rainfall and/or irrigation) and subtracting water losses (consumptive use) during the elapsed period.

One of the problems in using this method is making a reliable estimate of the daily consumptive-use rate for the crop grown. If research has already established an average daily consumptive-use rate for the same

crop in nearby areas, this rate should be used. Generally such data are not available, however, and the consumptive-use rate must be estimated. To arrive at an accurate estimate of the consumptive-use rate for any given day, it is necessary to correct the average rate for the weather conditions of that day.

The four principal climatological factors that influence a change in consumptive use for any given day are: (1) Average temperature, (2) percentage of possible sunshine hours or sunshine duration, (3) average relative humidity, and (4) average wind speed. Of the four factors, temperature and sunshine duration are by far the most significant. Temperature can easily be measured on the site with a reliable thermometer. The average of the high and low readings for a 24-hour period can be taken as the average temperature for that day. The same readings can often be obtained from a nearby Weather Bureau station. Either sunshine duration or cloudiness can be estimated visually with sufficient accuracy for ordinary farm irrigation. Relative humidity and wind speed are of minor significance and can be ignored without seriously affecting the data. They are difficult to measure, and measurements are not available from the Weather Bureau in most areas.

Variations from the average daily consumptive use caused by fluctuations in temperature and sunshine duration can be computed by the Penman procedure and can be used to modify average daily consumptive-use values. The modified values can then be tabulated in some convenient way, as shown in table 1-8. The applicable consumptive-use rate for any set of weather conditions for a given day can be read directly from the table.

The moisture-accounting method requires a daily measurement of rainfall at the site. A small, inexpensive rain gage is satisfactory if it is read carefully. It should be located away from buildings, trees, and high vegetation so that it accurately measures the amount of rainfall. It should be read early each morning.

Keeping the daily balance is a simple procedure, but it must be done each day. By knowing the daily values for rainfall, the estimated rate of consumptive use, and the amount of available water that can be depleted safely before irrigation, the daily balance can be computed in the following manner.

Computation must be started when it is certain that the soil is at field capacity, which it usually is on the day following a heavy rain or an irrigation. Then each morning the amount of available moisture in the soil is computed by subtracting the estimated consumptive use for the previous day from the previous morning's balance. The previous day's irrigation and rainfall, if any, is added to the previous morning's balance. Early morning (7 or 8 a.m.) has been selected as a convenient time to compute the daily balance since weather data for the previous 24 hours are usually available from local Weather Bureau stations and local radio programs at this time.

Table 1-8.--Values for daily consumptive use that reflect variations in temperature and sunshine duration for July

Location: Greensboro, N.C. Latitude: 36°-05' N. Crop: Alfalfa

Observed average daily temperature	Daily consumptive use for observed daily sunshine duration of--				
	0 hours	5 hours	8.9 hours (average)	10 hours	14.4 hours (maximum possible)
<u>° F.</u>	<u>Inches</u>	<u>Inches</u>	<u>Inches</u>	<u>Inches</u>	<u>Inches</u>
65	0.13	0.16	0.19	0.20	0.23
70	.13	.17	.21	.22	.25
75	.14	.18	.22	.23	.26
77.2 ¹	-	-	.23	-	-
80	.15	.20	.24	.25	.28
85	.16	.22	.26	.27	.30
90	.17	.23	.27	.28	.33

¹ Average.

When rainfall causes the daily balance to exceed the field-capacity level, the excess is presumed to be lost either to surface runoff or to deep percolation. Then the daily balance is recorded as the field-capacity level. Some rains may be of such high intensity that they cause surface runoff before the soil is filled to field capacity. When this occurs, investigations should be made so that the amount of moisture that entered the soil can be estimated. This amount should be entered instead of the total rainfall amount.

When the daily balance reaches the point at which soil moisture is depleted to the predetermined allowable limit, it is time to irrigate. Ignoring application efficiency, the amount of water to be replaced in the soil by irrigation is the amount that brings the moisture level up to field capacity. To arrive at the balance on the morning following irrigation, this amount is added. The balance is then computed daily until another irrigation is indicated. Table 1-9 shows the method of moisture accounting used for alfalfa during July at Greensboro, N.C., and is suggested for use elsewhere.

Table 1-9.--Moisture-balance sheet for scheduling irrigation

Farm John Doe Field No. 5 Crop Alfalfa Month July Year 1957
 County Guilford State North Carolina Soil type Silt loam
 Moisture-holding capacity in root zone 4.50 inches
 Net moisture to apply at each irrigation 2.25 inches¹

Day	Temperature			Observed sunshine	Estimated daily evapo- transpiration ²	Rainfall	Irrigation	Daily balance	Remarks: (Appearance of plant, height of plant, wind, etc.)
	Maximum	Minimum	Average						
	° F.	° F.	° F.	Hr.	In.	In.	In.	In.	
								1.48	Balance brought forward from 6/30.
1	85	65	75	14	0.26			1.22	
2	81	61	71	13	.24			.98	
3	86	59	72	14.5	.25			.73	
4	90	64	77	14.5	.27			.46	
5	91	69	80	10.5	.25	.26		.47	
6	85	63	74	14.5	.26			.21	
7	89	58	74	14.5	.26		2.25	2.20	
8	93	65	79	14	.28			1.92	
9	94	70	82	12	.27			1.65	
10	89	69	79	14.5	.28			1.37	
11	87	63	75	14	.26			1.11	
12	93	60	76	14	.26			.85	
13	95	66	80	13.5	.27			.58	
14	96	73	84	13.5	.29			.29	
15	93	70	81	10	.25			.04	
16	92	69	80	11	.26		2.25	2.03	
17	89	68	78	5	.19	1.63		2.25	1.22 inches lost
18	80	69	74	2	.16	.12		2.21	
19	85	66	75	11	.24			1.97	
20	87	62	74	14	.26			1.71	
21	90	67	78	14	.27			1.44	
22	92	69	80	11.5	.26			1.18	
23	93	72	82	9.5	.25	.11		1.04	
24	81	66	73	8.5	.21	.02		.85	
25	83	60	71	14	.25			.60	
26	83	59	71	13	.24			.36	
27	82	67	74	13	.25			.11	
28	86	62	74	13.5	.25		2.25	2.11	
29	88	63	75	14	.26			1.85	
30	92	64	78	12.5	.26			1.59	
31	93	67	80	13	.27			1.32	
Totals.....						2.14	6.75	1.32	Carry over to Aug. 1

¹ Based on replacing 2.25 inches of moisture when the 50-percent level has been reached.

² Values taken from table 1-10.

The moisture-accounting method has the obvious advantage of requiring no costly equipment and very little labor. Its accuracy depends on accurate estimates of the water-holding capacity of the soil, on accurate computation of the daily water-use rate, and on good judgment in adjusting the rate for each day's weather. As more consumptive-use data become available and practical methods of adjusting the daily use rate for climatological variations are developed, this method seems to have greater possibilities for determining when to irrigate than any of the other methods.

Using a few well-placed soil-moisture measuring units to supplement moisture accounting improves irrigation scheduling. The accounting procedure indicates the overall pattern of moisture depletion. The moisture-measuring units serve to check conditions at particular locations in a field as well as to indicate the depth to which rainfall or irrigation water has penetrated the soil. They provide a check on the accounting for the crop, soil, and weather conditions in a particular field in a particular year. They also are good tools to use in auditing the daily balance records for arithmetical mistakes and inaccurate consumptive-use rates.

Evaporation-Pan Method

Interest in using evaporation pans to schedule irrigation is growing. Research in various parts of the country shows a close relation between the rate of consumptive use by crops (evapotranspiration) and the rate of evaporation from a well-located evaporation pan. This correlation indicates that measurements of pan evaporation are accurate enough for scheduling irrigation. This method is cheap and simple.

Pruitt and Jensen have reported comparisons of actual consumptive use and pan evaporation for four crops at Prosser, Washington. They use three levels of moisture treatment--wet, medium, and dry. Three of their comparisons for the wet treatment and the period of good ground cover are shown in figure 1-25. The evaporation data are for a pan located about 3 miles south of the experimental site in an environment similar to that of the experimental site. The evaporation pan was 6 feet in diameter and 2 feet deep and was set in the ground with the rim about 2 inches above the surface. The water level was kept at between 2 and 4 inches from the top of the pan.

The good correlation shown was obtained by multiplying pan-evaporation data by a crop factor. Pruitt and Jensen report that during the early stages of plant growth, when plants are small and provide little ground cover, the measured consumptive use for sugar beets and potatoes is considerably lower than the average pan evaporation. In almost all later periods when the crop provides good ground cover, however, consumptive use is about equal to or greater than pan evaporation. The ratio for alfalfa varies throughout the season. During periods when cuttings are taken off, there is a consistent reduction in the ratio between consumptive use and pan evaporation as compared with periods when no cuttings are taken.

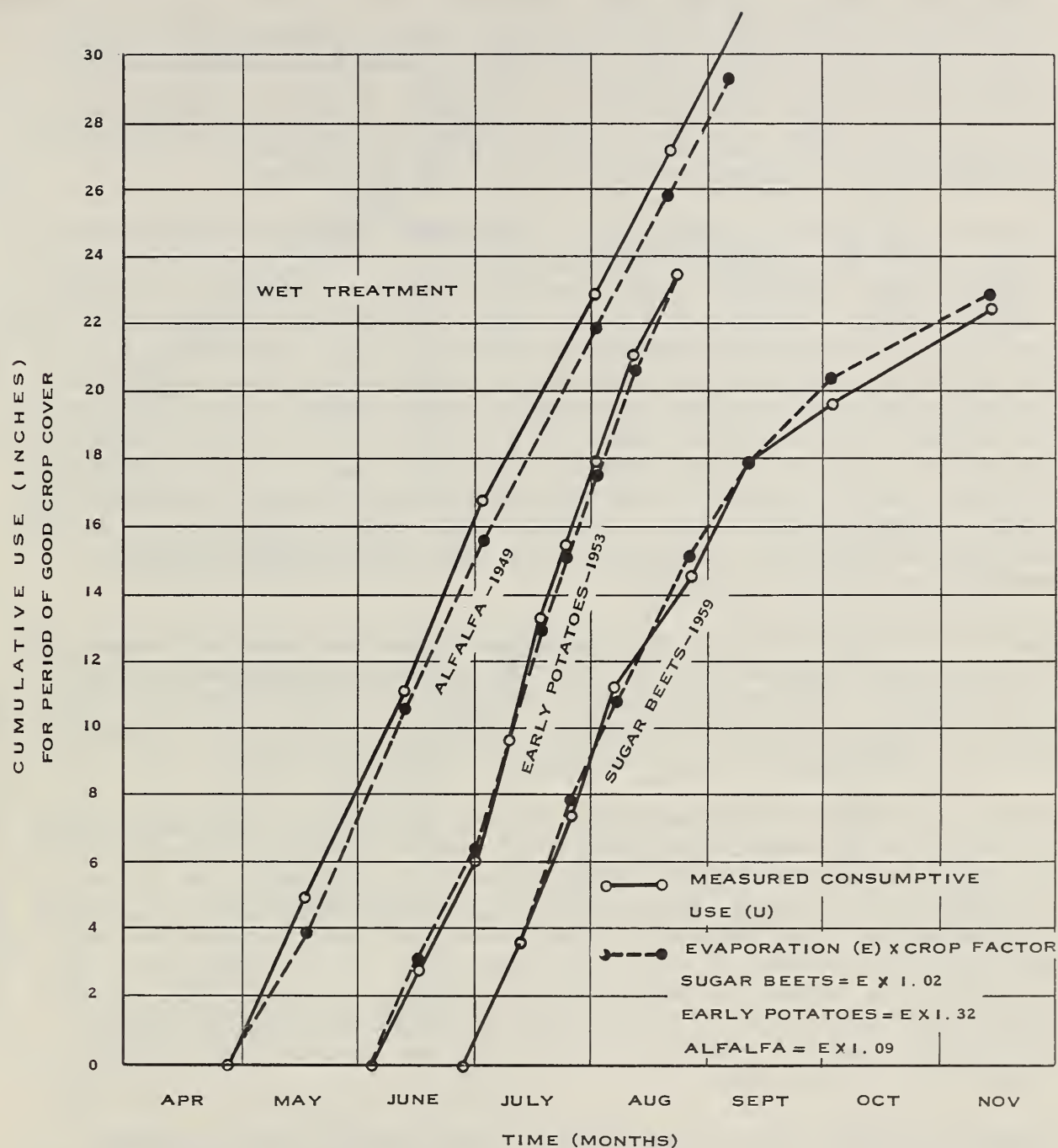


Figure 1-25.--Cumulative curves for measured consumptive use (U) and for evaporation (E) from a USDA BPI pan at Prosser, Wash. (Redrawn from Pruitt, W. O., and Jensen, M. O. Determining When To Irrigate. Agr. Engin. 36: 181-184. 1955.)

Pruitt and Jensen conclude that consumptive use dropped off with the dry moisture treatment but that the decrease was not large unless yields were materially lowered. The difference between U and adjusted E was slightly more for alfalfa than for row crops, probably because of the effect of cuttings. The favorable correlation between E modified by a crop constant and U indicates promise of the development of evaporation equipment that a farmer can use to tell when to irrigate.

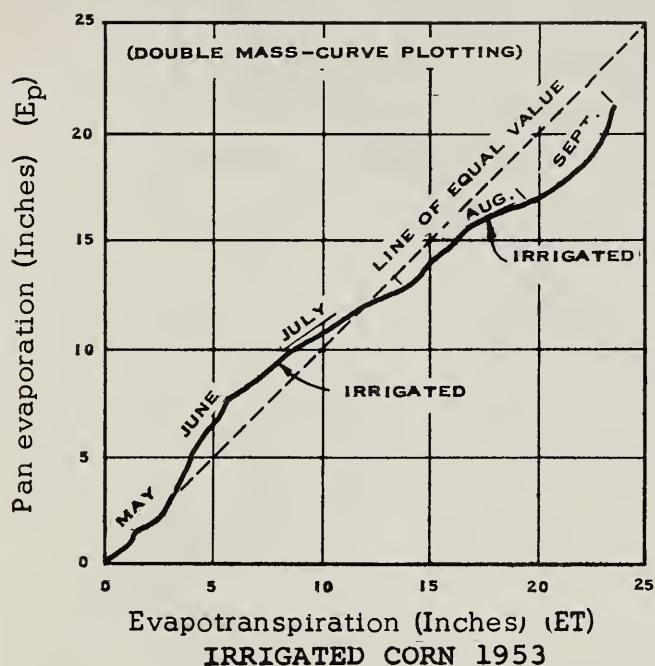
Harrold got similar results at the Coshocton, Ohio, Hydrologic Station (fig. 1-26). The irrigated corn was grown in 1953 on lysimeter Y102 on land having a 12-percent east slope. The alfalfa data are for alfalfa-timothy grown on lysimeter Y102 in 1952. Correlation constants for these two sets of data are shown for the various months in the growing season. The data for irrigated corn indicate a relationship between evapotranspiration and pan evaporation during July and August, a period in which an adequate soil-moisture content was maintained by irrigation. Harrold points out that in May and June the relation seems to be influenced by surface moisture and that evaporation is relatively more important then since transpiration is low. A sunken 6-foot BPI pan was used to get the evaporation data. The consumptive-use data were from the Coshocton weighing-recording lysimeters.

Harrold concludes that if an irrigation farmer has evaporation-pan data on a site and has factors for deriving therefrom day-by-day moisture-use values for his crop throughout the season he may be able to keep a set of books on available moisture--rain and irrigation on the plus side and consumptive use on the minus side of the ledger.

Figure 1-27 shows the relation of the average daily evapotranspiration for ryegrass to evaporation from a U.S. Weather Bureau class-A pan by months as determined by Pruitt and Angus from studies at the University of California at Davis. The average daily evapotranspiration by months plotted against pan evaporation indicates that there is a close relation throughout the season if dry, north-wind days are not considered. On such days the departure from normal is extreme, especially in the fall. Figure 1-27 also shows that the ratio of evapotranspiration to pan evaporation ranges from about 0.73 to 0.8 and that the average is 0.77 from April to September.

Vaughn E. Hansen and his associates at Utah State University have experimented with the relation of evapotranspiration to pan evaporation. Their work indicates that measuring evaporation is a practical approach that can be used by farmers to schedule irrigation. In addition to using a Weather Bureau pan, they found that measurements from a 50-gallon oil drum buried in the soil give a reasonable correlation but that the ratios are somewhat higher than those shown by Weather Bureau pan data.

The location of the evaporation pan is important. The data from Davis, Calif., shown in figure 1-28 indicate that the wetness or dryness of the area immediately surrounding the pan is highly important. The U.S. Weather Bureau recommends that the site be nearly level, sodded, and

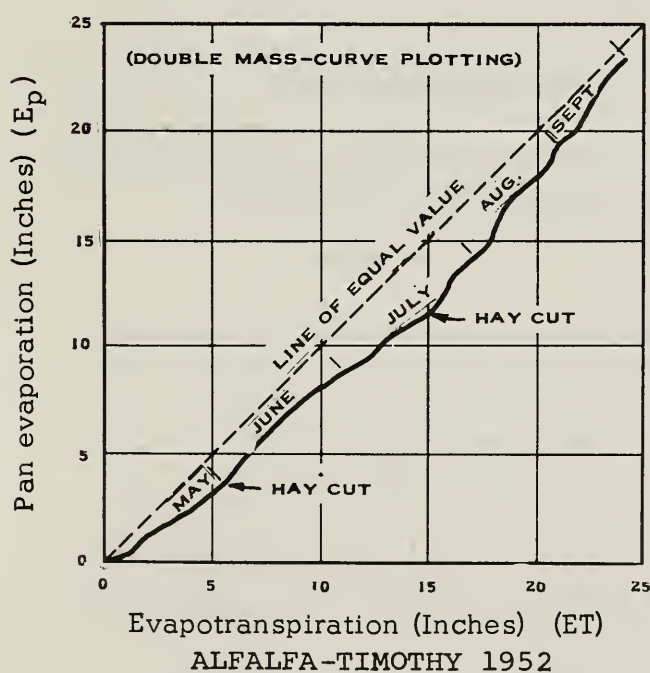


May 1-31 $ET = 1.0E_p$

June 1-30 $ET = 0.5E_p$

July 1 - Aug. 31 $ET = 1.5E_p$

Sept. 1-15 $ET = 1.2E_p$



May 1-31 $ET = 1.6E_p$

June 1- July 15 $ET = 1.1E_p$

July 16 - Sept. 30 $ET = 0.8E_p$

Figure 1-26.--Relation of measured evapotranspiration for irrigated corn and alfalfa-timothy to evaporation from a BPI-type pan at Coshocton, Ohio. (Redrawn from Harrold, L. L. Evapotranspiration Rates for Various Crops. Agr. Engin. 36: 669-773. 1955.)

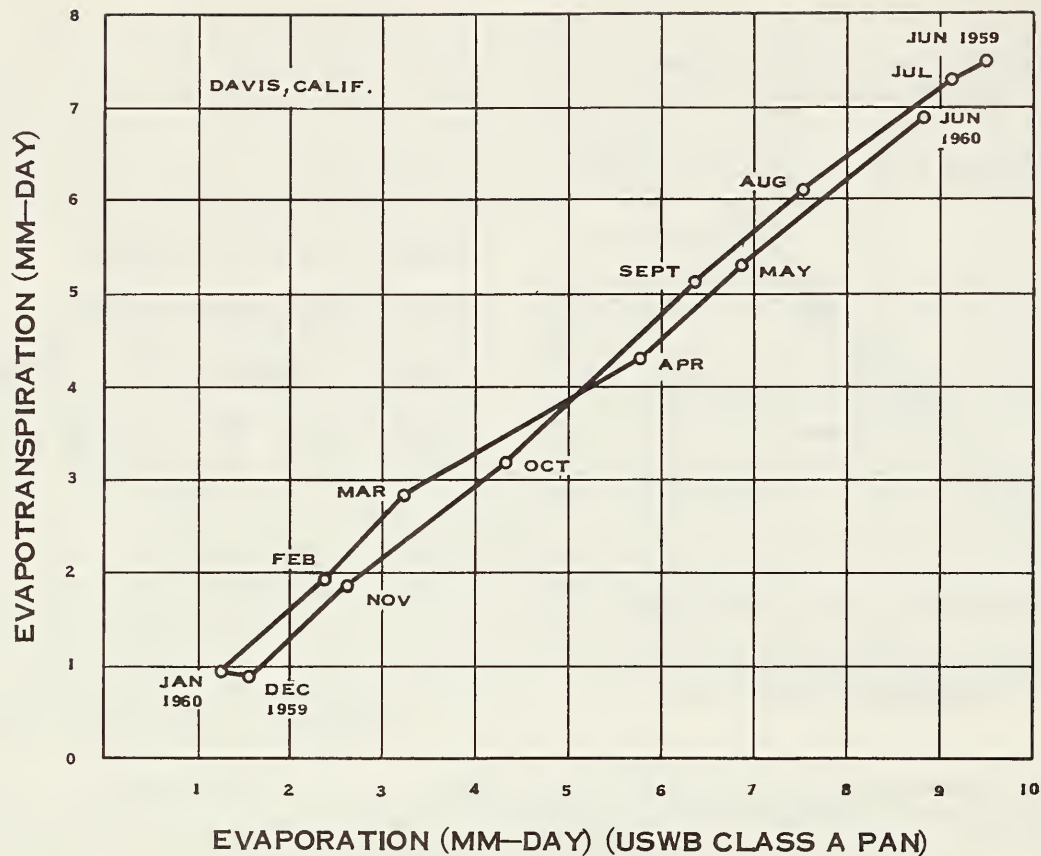


Figure 1-27.--Relation of average daily evapotranspiration for ryegrass to evaporation from a U.S. Weather Bureau class-A pan by months at Davis, Calif.

free of obstructions. Trees, buildings, and shrubs should be no closer to the pan than two times and preferably four times their height above the pan. Weeds and grass in and around the pan should be mowed often enough to keep them below the level of the pan. The pan should be free of any obstructions that cast shadows over it during any part of the day other than brief periods near sunrise or sunset. At reservoirs a site on the upwind side is preferable, based on the prevailing direction of the strongest winds. The pan should also be far enough away so that waterdrops from spillways or those picked up by strong onshore winds are not deposited in the pan.

The effect of the stage of plant growth on the ratio of evapotranspiration to pan evaporation is shown in figure 1-29, which is based on studies of sugarcane in Hawaii. After the fourth month, the ratio is between 1 and 1.2. But for the first 4 months, it is between 0.4 and 1. This study further indicates that irrigation can be scheduled from pan-evaporation data.

The factor (ratio) for any crop seems to depend mostly on foliage characteristics, stage of growth, environment, and geographical location.

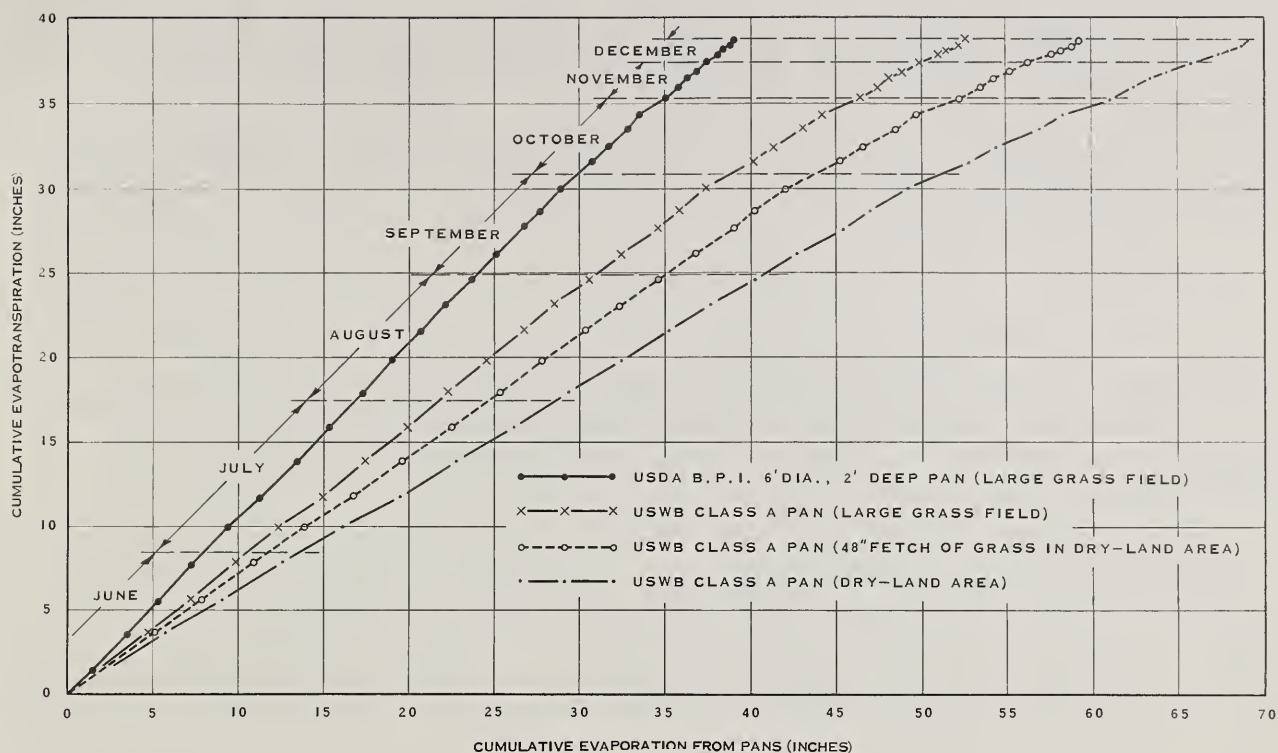


Figure 1-28.--Relation of cumulative evapotranspiration for perennial ryegrass to evaporation from two types of pans in different environments at Davis, Calif.

**AVERAGE EVAPOTRANSPIRATION/PAN EVAPORATION RATIOS
FROM THREE FIELDS COMPARED TO AGE OF CANE**

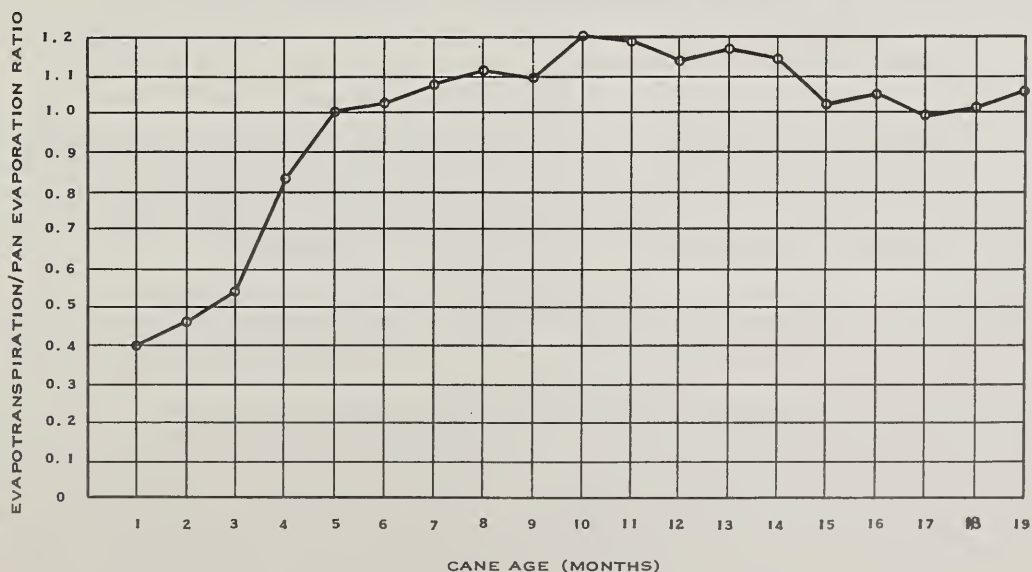


Figure 1-29.--Ratio of average evapotranspiration to pan evaporation for three fields by age of sugarcane. (Redrawn from Chang, Jen-Hu. Microclimate of Sugarcane. Hawaii Planters' Rec. 56(3): 195-225. 1961.)

The effect of some individual factors is shown in figures 1-25, 1-26, and 1-29. Jensen, Middleton, and Pruitt developed the crop factors shown in table 1-10 for several crops grown in central Washington.

Table 1-10.--Crop-factor values for computing estimated consumptive use from pan-evaporation data for several crops grown in central Washington¹

C r o p	Crop factor ²
Corn, grapes, and clean-cultivated peach orchard.....	0.85
Alfalfa, grains, Ladino-grass pasture, and sugar beets.....	.95
Beans, peach orchard with cover crop, and potatoes.....	1.00
Apple orchard with grass cover.....	1.05

¹ From Jensen, M. C., Middleton, J. E., and Pruitt, W. O. Scheduling Irrigation From Pan Evaporation. Wash. Agr. Expt. Sta. Cir. 386, 14 pp. 1961.

² To provide a safety margin for field use, these recommended values are 0.05 larger than the average measured values.

It must be remembered that evaporation-pan data are approximations of consumptive use and are not measurements of soil moisture. The amount of soil moisture used in a given period must be calculated. This can be done by applying the factor for the crop to be irrigated to the amount of water, or depth of water, evaporated from the pan during that period. This calculated amount then represents the soil moisture (in inches) used by the crop. In other words,

$$\text{Evapotranspiration (U)} = \text{pan evaporation (E)} \times \text{crop factor.}$$

In using evaporation-pan data to schedule irrigation, it is necessary to know only the amount of moisture to be replaced at each irrigation. It is then a simple matter to determine what depth of water must be evaporated from the pan to equal the amount to be replaced in the soil.

Jensen, Middleton, and Pruitt based their method for scheduling irrigation from pan-evaporation data on a "water account" of the moisture in the soil. Deposits to the account are from irrigations and precipitation. Withdrawals from the account are from crop consumptive use (evapotranspiration). Crop consumptive use is determined by multiplying measured evaporation from an evaporation pan 4 feet in diameter by the established constant (crop factor) shown in table 1-10. The pan should be located in an area 50 x 50 feet on which there is a lawn-type cover that is kept green and clipped like a lawn. The station should be fully exposed to sunlight and wind and be within a field in which the established crop, such as pasture or alfalfa, is no higher than the top of the pan. A water-supply tank is used. By means of a float valve the

water level is kept 2-1/2 inches from the top of the pan. Rainfall is measured by a rain gage. Significant amounts of rainfall are considered in addition to evaporation. For runoff-producing storms, the wasted water is deducted from the reported rainfall.

M. D. Shaw at Pennsylvania State University found that using evaporation data from 5-quart oil cans 9-1/2 inches high is a successful farm method of determining when to irrigate. The oil cans are painted with metallic zinc paint for uniformity and to prevent rusting. Evaporation from a can set with one-fourth of its height in the ground is very close to that from a standard Weather Bureau evaporation pan. These cans serve as rain gages as well as evaporation cans. The cans are filled to a 7-inch depth when it is known that the soil-moisture level is at field capacity. When the water level in the can has dropped an amount equal to the amount of water to be applied at each irrigation, it is time to irrigate. The can should be filled to the starting level after each irrigation or after a rainfall that brings the soil-moisture level up to field capacity. Small rains add water to the pan as well as to the soil, keeping both in balance. After an intense rain that produces rapid runoff, it is necessary to make the best estimate possible of the soil-moisture level.

The standard Weather Bureau evaporation pan shown in figure 1-30, which is generally used in research, probably is too cumbersome to be practical for most irrigators to use and its installation is expensive for the small-scale irrigator. A simpler type of evaporation pan that provides fairly close correlation is needed for farm use. The 50-gallon oil drums used by Hansen and the 5-quart oil cans used by Shaw indicate that relatively cheap pans can be used provided they are well located and the evaporation data are correlated with the consumptive use of the crops to be irrigated.

Evaporation-pan data, like the accounting method, indicate the probable overall pattern of moisture depletion for a field. A few well-placed soil-moisture-measuring units are valuable for checking the crop factors used and provide a basis for adjusting a factor to the particular soil, crop, and weather conditions in each year. These units can also be used to check moisture conditions at troublesome spots in a field as well as to indicate the depth to which rainfall or irrigation water penetrates the soil.

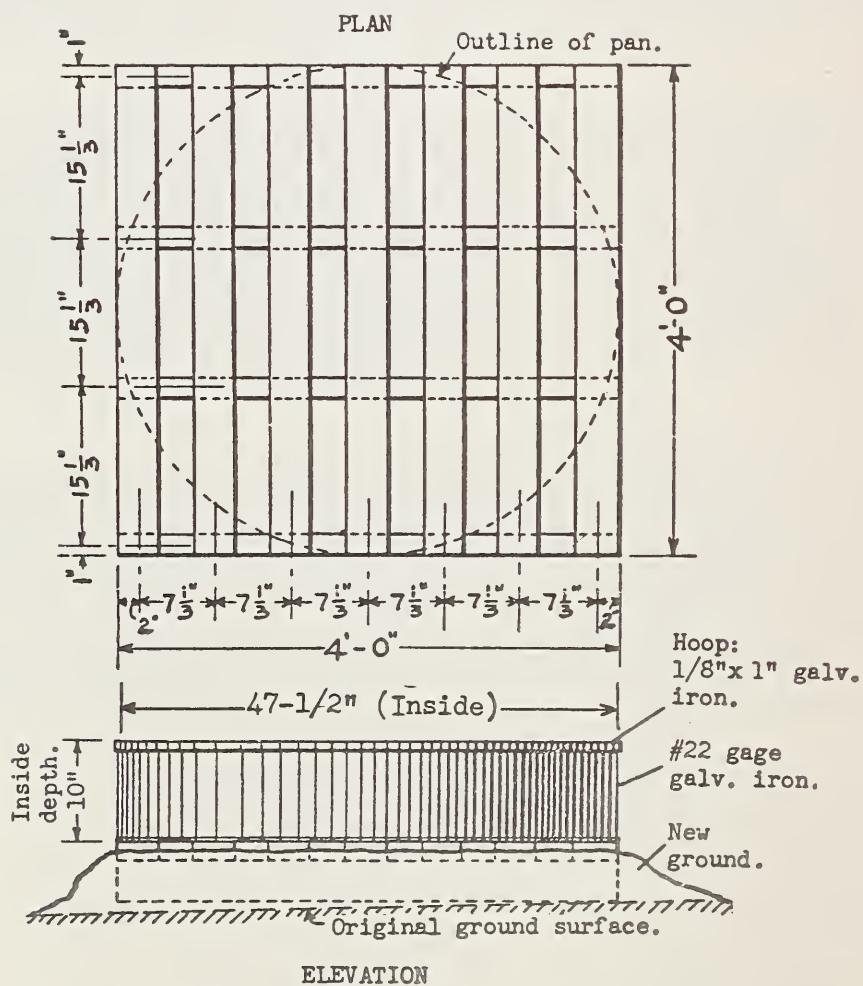
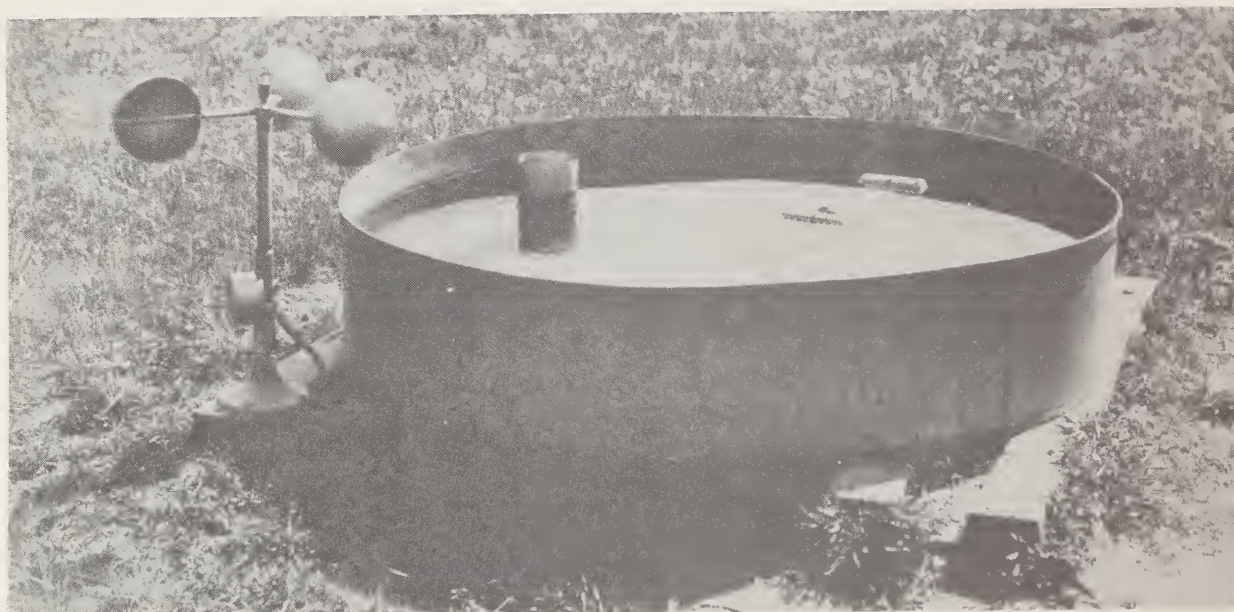


Figure 1-30.--Standard Weather Bureau evaporation pan. (From U.S. Weather Bur. Instructions for Climatological Observers. 10th ed. rev. 1955.)

